# BODY MASS INDEX AND ITS EFFECT ON PLANTAR PRESSURE IN OVERWEIGHT AND OBESE ADULTS

A Thesis submitted by

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# ABSTRACT

The proportion of overweight or obese adults is creating a growing problem throughout the world. Overweight and obesity have a significant influence on gait, and often cause difficulty. There is evidence to suggest that being overweight or obese places adults at a greater risk of developing foot complications such as osteoarthritis, tendonitis, plantar fasciitis, and foot ulcers. Increasingly, pressure ulcers have become a serious health problem. The purpose of this research is to investigate the effect of body weight on the feet, and to investigate the use of simulated body mass to study the effect of variable body mass on the foot plantar in adults aged 24 to 50 years of age while walking at a self-selected pace. A series of studies were undertaken to achieve the above purpose. The research involved: **1)** assessing dynamic foot plantar pressure characteristics in adults who are normal weight, overweight or obese; **2)** studying the gait impact of increased simulated body weight (SBW); and **3)** evaluating the spatial relationship between the trace of the centroid of the area of contact with heel strike, midstance, and toe-off phases for the SBW groups. F-Scan in-shoe systems were utilised to gather the foot pressure data.

The first study sought to investigate the effect of different body mass index (BMI) levels on plantar pressure distribution during walking, collection in fifteen voluntary participants were recruited. The BMI participants were divided into three groups (healthy, overweight and obese). The foot was divided into ten regions: heel (H), midfoot (MF), first metatarsal head (1MH), second metatarsal head (2MH), third metatarsal head (3MH), fourth metatarsal head (4MH), fifth metatarsal head (5MH), hallux ($1^{st}$T), second toe ($2^{nd}$T), and third to fifth toes ($3^{rd}$-$5^{th}$T). For each region, the following parameters were calculated: force (F), contact area (CA), contact pressure (CP), pressure time integral (PTI) and peak pressure (PP). The mean of the three repetitions of each subject was computed, and statistical procedures were performed with these mean ± standard deviation (SD) values**.** This study showed that the obese group had higher plantar pressure parameter values compared to the other two groups (overweight and healthy) for the ten different foot regions. The study observed significant changes in the parameters in the H and MHs (e.g. 2MH and 3MH) foot regions. The forefoot appears to be more sensitive to weight-related pressure under the foot than the rearfoot. Findings from this study indicate that being overweight or

obese increases foot pressure measures, even for individuals with similar body features. Higher BMI values correlate with a higher load on the foot during walking in males. These findings have implications for pain and discomfort in the lower extremity in the obese while participating in activities of daily living such as walking.

The second study investigated the effect of the research methodology involving the simulation of body weight (SBW) with additional weight, adding 10, 20, 30 kg to each participant's body weight on plantar pressures. The sample comprised 31 adult males; each subject walked four times. The first walk was without any external weight (NBW, 0 kg), the second walk was with a weight of 10 kg, the third walk was with a weight of 20 kg and the last walk with a weight of 30 kg in the vest. The foot was divided into ten regions and for each region, the parameters were calculated the same way as the first study. At the end of this study it should be noted that SBW groups subjected to load have shown changes in foot plantar measure values compared to the NBW group. Most of the differences were found under H, MHs, 1$^{st}$T and MF regions in the most clinically relevant parameters in SBW groups compared to the control group; the SBW groups showed higher values of plantar pressure. The results of the ICC showed a generally good to an excellent level of reliability, the quality of which was dependent on the regions of the foot and the variables investigated with SBW loads. This experiment pointed out that an insole pressure system is a reliable tool for evaluating foot plantar forces and pressures throughout the walk. The plantar pressure measures can be used in relative assessments, as the measures of repeatability are favourable for the measures and foot zones generally utilised in the study of people with clinical problems like neuropathic diabetics.

In the final study, associations were investigated of the centroid (coordinates x-axis and y-axis) of the area of contact captured between normal (NBW) and simulated body weight (SBW) changes. The same 31 adult males who enrolled with the SBW tests were used to collect the centroid of the area of contact with the surface. This was located by calculating the geometric centre of a set of cloud points having the lowest z coordinate value. In this part, a foot pressure sensing insole was used to calculate the moment of heel strike, midstance and toe-off phases. Data were analysed descriptively (mean ± SD only). The outcome of this study, relating to specific individual characteristics of the centroid trace of the plantar contact area was compared with the heel strike, midstance, and toe-off phases for the SBW group with the NSBW group. X-axis and y-axis coordinates in the heel strike, midstance and toe-off phases under SBW with 30, 20, 10 kg had higher mean values compared to NSW. The x-axis and y-axis coordinates had mean values of 11.76, 9.68, and 7.76 mm; while the y-axis coordinates had mean values of 11.96, 9.89, and 8.18 mm. Moreover, x-axis and y-axis coordinates were assessed in the midstance phase under SBW with 30, 20, 10 kg with means of 6.59, 5.48, and 4.50 mm; while the y-axis coordinates had mean values of 6.38, 5.41, and 4.41 mm. In addition, x-axis and y-axis coordinates were assessed in the toe-off phase under SBW (30, 20, 10 kg) with mean values of 11.56, 9.67, and 7.97 mm; while the y-axis coordinates had mean values of 11.51, 9.39, 8.02 mm, respectively. X-axis and y-axis coordinates had mean values in relation to NBW in three phases: heel strike of 5.47 and 6.15; midstance of 2.99 and 3.05; and toe-off of 6.04 and 5.82, respectively. The x-locate and y-locate change can be calculate the change in rotation of the ankle joint. As the data was normalised according to the total time taken for the loading phase of the gait, the y-locational change was due partly to the extra weight, which could increase the time of lifting the foot. Therefore, the results showed that the x-locate and y-locate change can help to calculate the change in the rotation of the ankle joint.

The project has shown that it is possible to demonstrate that obese people will, throughout their lives, adopt ways to effectively execute a particular activity. This finding provides a foundation for future clinical trials which could assist in preventing foot complications and could assist in the design of appropriate interventions to promote healthy outcomes for these adults. The simulated body weight resulted in a variation in plantar pressure distribution. Because the human foot adapts itself to any simulated condition, knowledge of the variation of pressure distributions of both feet can provide input for suitable guidelines for biomedical engineers. To promote the prevention of likely injury to the feet of overweight and obese people, the results of this study demonstrate the need to develop strategies which could include the building of an insole (orthosis) that absorbs foot plantar pressure.

# Certification of Thesis

This thesis is entirely the work of Suhad Kareem Rahi Al-Magsoosi except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Dr. Albert Chong

Principal Supervisor: ____________________

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Associate Supervisor: ____________________

Student's and supervisors' signatures of endorsement are held at the University.

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Finally, I would like to dedicate this dissertation to my family: my parents, sisters and brothers who have been a continual source of inspiration, support and encouragement. Without them all I may not have successfully made it to the end of this journey.

# CONTRIBUTIONS TO THEORY AND PRACTICE FROM THIS RESEARCH

This research covers a relatively wide range of topics relating to overweight and obesity and lower limb foot plantar sole issues, sustainability, causes, consequence and insole system technique. They have an increased susceptibility to overuse injuries and the tendency to withdraw from weight management programs that involve physical activity. Therefore, we believe that before overweight/obese adults join any physical activity weight-management program. A summary of the main contributions to practice arising from this research include:

- An in-depth understanding of the foot and ankle in terms of balance and injury.
- Data collection from 46 subjects with different body weight (normal, overweight and obese) and normal self-select gait.
- Consideration of the efficiency of insole systems.
- A novel approach to simulating the long-term relationships between body weight and foot plantar pattern. This simulation approach appears to be robust and may be used to assist further studies in this space and to assist in decision-making.
- Practical recommendations (based on laboratory experiments) for foot protection and management to increase human health.
- The outcomes of this study can be used to enable further research into areas like injury prevention and balance monitoring in walking based on weight.

# LIST OF RELATED PUBLICATIONS

## JOURNAL

**Suhad K. R. Al-Magsoosi** & Albert K. Chong, 2019. ‘Foot loading pattern variations between normal weight, overweight, and obese adults aged 24 to 50 years’. *Journal of Biosciences and Medicines*. Vol.07 No.05, pp.34-49. DOI: 10.4236/jbm.2019.75007.

Albert K. Chong & **Suhad K. R. Al-Magsoosi**, 2019. ‘Development of an Index for Drop-Foot Severity of DPN Patients’. *Journal of Biosciences and Medicines*. Vol.7 No.5, PP. 61-64. DOI: 10.4236/jbm.2019.75009.

## CONFERENCE

**Al-Magsoosi, S.K.** & Chong, A.K., 2019, March. Advanced Foot Pressure Technology for Demonstrating the Influence of Over-weight and Obesity on Ankle Joint. In Proceedings of the ICISS 2019 Proceedings of the 2019 2nd International Conference on Information Science and Systems. Tokyo, Japan. (pp. 195-199). ACM. DOI>10.1145/3322645.3322661.

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# ABBREVIATIONS

| | |
|---|---|
| AIHW | Australian Institute of Health and Welfare |
| ANOVA | Analysis of variance |
| BMI | Body Mass Index |
| CA | Contact area |
| CDC | Centres for Disease Control and Prevention |
| $cm^2$ | Square Centimetre |
| COM | Centre of mass |
| COP | Centre of pressure |
| CP | Contact pressure |
| CV | The coefficients of variation |
| CT | Contact time |
| F | Force |
| FTI | Force-time integrals |
| GRF | Ground reaction force |
| H | Heel |
| Hz | Hertz |
| ICC | Interclass Correlation Coefficient |
| IPP | Instant of peak pressure |
| Kg | Kilogram |
| kPa | Kilopascals pressure measurement unit |
| kPa.s | Kilopascals second |
| Lf | Left foot |
| 1MH | First metatarsal head |
| 2MH | Second metatarsal head |
| 3MH | Third metatarsal head |
| 4MH | Fourth metatarsal head |
| 5MH | Five metatarsal head |
| m | Metre |
| MF | Midfoot |
| Max | Maximum |
| mm | Millimetre |
| n | Number |
| $N/cm^2$ | Newton per square centimetre pressure unit |
| N | Newton |
| NBW | Normal body weight, 0 kg |
| PF | Peak force |
| PP: | Peak pressure |
| PT | Pressure time |
| PTI: | Pressure time Integral |
| P-value | level of significance within a statistical hypothesis test |
| Rf | Right foot |
| r-value | Correlations value |
| SBW | Simulate body weight (by additional weight 10, 20, 30 kg) |
| SD | Standard deviation |
| SPSS | Statistical Package for the Social Sciences |
| $1^{st}$T | Hallux |
| $2^{nd}$T | Second toe |
| $3^{rd}$-$5^{th}$T | 3–5Toes |
| WHO | World Health Organization |
| % | Percentage |

# CHAPTER 1: INTRODUCTION

# 1. INTRODUCTION

## 1.1. Introduction

This chapter will provide an outline of the background and research motivation by defining the research gaps and the research aims and objectives. It will also explore contribution of this research to the relevant body of literature. The chapter concludes with a brief thesis outline.

## 1.2. General overview

The increasing number of overweight and obese adults has become a significant public health concern worldwide and is associated with both increasing health care costs and clinical problems (Sheffler et al., 2014; Anandacoomarasamy et al., 2007). Increasing levels of obesity are associated with rising rates of diabetes (Mokdad et al., 2003). Furthermore, 41 million children under the age of five years and, over 340 million children and adolescents aged five to nineteen years, are overweight or obese (WHO, 2016).

Overweight and obesity are associated with numerous other medical conditions such as painful feet, flat feet, Charcot foot, foot pathology (ulcer), a high incidence of osteoarthritis, and symptomatic complaints in the joints of the lower extremities (Wearing et al., 2006; Stuck et al., 2008; Riskowski et al., 2011; Periyasamy et al., 2012).

Body weight is considered to have the most significant impact on the structure and functioning of the foot. Overweight and obesity and their influence on foot arches have been dealt with, especially in the context of flat foot incidence (Mickle et al., 2006; Villarroya et al., 2009; Chang et al., 2010).

A high prevalence of disabling foot pain and the incidence of foot deformities, poor foot health, and the presence of other pain like lower back, hip, leg, and knee pain, have been associated with adults who are overweight or obese (Butterworth et al., 2012; Mickle and Steele, 2015). More recent investigations by Butterworth et al. (2012) have found that the foot is not immune to the effects of obesity, with a recent systematic review of 25 studies involving 93,224 participants concluding that obesity is strongly associated with non-specific foot pain in the general population.

A possible explanation for the relationship between obesity and foot pain is that excess body weight leads to greater mechanical loading of the foot. Indeed, a link between increased force and pressure under the foot and obesity has been reported (Hills et al., 2001). A case–controlled study of 80 subjects with chronic heel pain syndrome and 80 age- and gender-matched control subjects found that those with chronic heel pain syndrome were three times more likely to be obese and four times more likely be flatfooted (Irving et al., 2007).

Recently, foot and ankle pathologies such as plantar fasciitis (Riddle et al., 2003) and plantar heel pain (Irving et al., 2007; Prichasuk, 1994), have become more prevalent in adults due to increased body weight. Some research studies have investigated the relationship between plantar pressure and foot pain, finding a clear association between them. It has been demonstrated that load carriage can adversely affect a number of physiological parameters, such as gait (Birrell & Haslam, 2009; LaFiandra et al., 2003; Smith et al., 2006). Some research studies in western countries have revealed that plantar pressure is increased in obese adults whose body mass index (BMI) is > 30kg/m$^2$ (Gravante et al., 2003; Hills et al., 2002; Birtane & Tuna, 2004). Around the world, it is estimated that two million people present with chronic plantar heel pain each year. For these people, the number one cause is plantar fasciitis (Thing et al., 2012). One of the concerns with the high prevalence of obesity is its association with an increased risk of falling. Each year, obese adults fall almost twice as frequently (27%) as their non-obese counterparts (15%) (Wu & Madigan, 2014). An important reason for falling in obese people is the loss of balance due to disrupted plantar sensitivity of the foot (Gravante et al., 2003).

Overweight and obesity influence plantar pressure distribution (Mickle et al., 2006; Phethean & Nestr, 2012; da Rochaet al., 2014). These effects, caused by obesity, are explained by the effect of weight on the foot structure. The literature includes studies reporting that excessive weight and increased BMI are related to a decrease in the arch of the foot and pes planus, changes in the plantar fat pad, biomechanical changes in the feet, and increased plantar pressure while standing and walking (Butterworth et al., 2012; Song et al., 2015).

The foot of an adult who is overweight or obese may differ in structure and function compared with the foot of a healthy weight individual due to alterations in morphology, soft tissue properties and functional capability (Dowling et al., 2001; Hills et al., 2002; Riddiford-Harland et al., 2011). Specifically, lower longitudinal arch heights (Gilmour & Burns, 2001; Gravante et al., 2003; Mickle et al., 2006) and greater foot lengths and girths (Mickle & Steele, 2015; Mickle et al., 2006) are evident in the feet of adults and children who are obese compared with healthy groups. As some research does not differentiate between overweight and obese individuals, the morphology and function of the feet of adults who are overweight are yet to be widely and thoroughly investigated independently from those of obese adults (Mauch et al., 2008).

Obesity also results in an increase in the ground contact area of the feet, altering the plantar pressure distribution and inducing pressure peaks in certain parts of the foot (Lee, 2009, Dowling et al., 2001). Peak plantar pressure is the highest pressure registered on each part of the foot, and its evaluation provides a strong clinical tool for understanding the structural and functional consequences of obesity (Filippin et al., 2007). The most negative consequences of being overweight or obese are that individuals often exhibit greater posture deficits (Gilleard & Smith, 2007; Greve et al., 2007) and gait alterations (Ko et al., 2010; Segal et al., 2009; Lai et al., 2008). The following sections discuss different gait analysis components.

## 1.3. Overview of clinical gait analysis (gait characteristics)

This section discusses gait analysis components. Comprehensive gait analysis is generally used for the assessment of a patient with a movement disorder. There are three components to gait analysis:

The first component is the spatiotemporal data: Spatiotemporal data provide a basic quantitative description of time and distance parameters during walking that involve: stride length, step length, stride width, step width, cadence, stride time, step time, walking speed (velocity) and phases (stance/swing).

The second component is kinematic parameters: Kinematic parameters give information about body motion, position, moments, and acceleration of body segments (joint angles like trunk angle, hip angle, knee angle and ankle angle). Track or trace coordinates (X, Y, and Z) and orientation are also considered. These are important because they reveal the significant effect of obesity on mechanics during walking.

The third component is kinetic parameters: Consideration of kinetic parameters includes kinetic factors; the term to describe gait with the force acting on the body including evaluating joint loading by calculating ground reaction force (GRF), pressure patterns, joint powers, joint forces momentum and torque (Winter, 2005). Therefore, spatiotemporal, kinematic and kinetic parameters have been researched as the main parts of the human gait. A thorough understanding of obesity on gait parameters is becoming more important as its effect on health status is gaining increasing significance. The next section will discuss how obesity affects walking.

## 1.4. Alterations in gait due to overweight and obesity

Numerous researchers have investigated the impact of higher body mass and BMI on gait characteristics (spatiotemporal, kinematic and kinetic), generally.

### 1.4.1 Spatiotemporal

First, spatiotemporal studies have shown there to be biomechanical differences between adults of healthy weight and those who are obese:

- Changes to the temporal-spatial gait parameters include decreased or shorter stride length (Hills & Parker, 1991; Spyropoulos et al., 1991; de Souza et al., 2005; Russell et al., 2010; Browning & Kram, 2007; Ko et al., 2010; Runhaar et al., 2011; Lai et al., 2008; DeVita & Hortobágyi, 2003; Messier, 2010) which has been related to reduced plantar flexion after initial contact for weight acceptance (Spyropoulos et al.,1991; Browning & Kram, 2007);
- Increased body mass height contributes to shorter step lengths (de Souza et al., 2005; Da Silva-Hamu et al., 2013; Kirtley, 2006; DeVita & Hortobágyi, 2003);
- Greater stride width (Hills & Parker, 1991), most likely due to increased inner thigh adipose tissue;

- Greater step width (Spyropoulos et al., 1991; de Souza et al., 2005; Browning& Kram, 2007; Hills & Parker, 1991; Huang et al., 2013; Dufek et al., 2012; Ko et al., 2010; Sarkar et al., 2011). Which can mainly be attributed to excessive adipose tissue between the obese individual's inner thighs, altering the angular components of the gait. For instance, step width was twice as wide as for the non-obese participant (Browning & Kram, 2007; Hills & Parker, 1991; Sarkar et al., 2011; Spyropoulos et al., 1991);
- A lower cadence of walking (Hills & Parker, 1991; Gill, 2015; Da Silva-Hamu et al., 2013; Kirtley, 2006);
- Slower velocity of walking (Chow et al., 2005; Ehlen et al.,2011; Da Silva-Hamu, et al., 2013; Kirtley, 2006; Hills &Parker, 1991; Malatesta, et al., 2009; Freedman Silvernail, et al., 2013; Ko et al., 2010; Hergenroeder et al., 2011; Spyropoulos et al., 1991; de Souza et al., 2005; Segal et al., 2009; Wearing et al., 2006; Runhaar et al., 2011; Lai et al., 2008; DeVita & Hortobágyi, 2003; Messier, 2010; Browning et al., 2013; Browning et al., 2009; Browning & Kram, 2007; England & Granata, 2007; Silvernail et al., 2013; Russell et al., 2010);
- Longer stance phase duration (Hills & Parker, 1991; Dufek et al., 2012; Lai et al., 2008; Spyropoulos et al., 1991; DeVita & Hortobágyi, 2003; Amiri et al., 2015, Browning & Kram, 2007; Lai et al., 2008). Which is important to increase stability therefore, obese adults tend to spend more time in the stance phase, with reduced time spent in the swing phase duration (Martin & Nelson, 1986; Dufek et al., 2012; Spyropoulos et al., 1991; Błaszczyk et al., 2011; Browning & Kram, 2007; DeVita & Hortobágyi, 2003);
- Longer period of double support phase compared to the healthy group (Martin & Nelson, 1986; Spyropoulos et al., 1991; Chow et al., 2005; Błaszczyk et al., 2011; DeVita & Hortobágyi, 2003; Browning & Kram, 2007; Lai et al., 2008; LaRoche et al., 2011; Hills & Parker, 1991; Huang et al., 2013; Dufek et al., 2012).

All of these make obese individuals walk more slowly than healthy individuals. The next section investigates the kinematic differences found for healthy weight and obese participants.

### 1.4.2. Kinematic factors

Kinematic factors are important because they reveal the significant effect of obesity on walking mechanics. During walking, obese adults have a more extended knee during early stance along with a greater pelvic obliquity during late stance (Lerner et al., 2014):

- The range of motion (ROM) is limited at the knee, hip, and ankle during walking (Gill, 2015; Ling et al., 2009; Lyytinen et al., 2013; Park et al., 2010);
- During level walking, significantly greater peak tibiofemoral contact forces are experienced due to greater muscle forces (Lerner et al., 2014; Haight et al., 2014);
- Differences can be detected in the hip joint (Spyropoulos et al., 1991; DeVita & Hortobágyi, 2003; Lai et al., 2008; Lerner et al., 2014), the knee joint (Browning & Kram, 2007; Lai et al., 2008; Segal et al., 2009; Russell et al., 2010; Lerner et al., 2014), and the ankle joint (Spyropoulos et al., 1991; Messier et al., 1994; de Souza et al., 2005; Lai et al., 2008; Vismara et al., 2007);
- Differences in the sagittal and frontal plane lower extremity joint mechanics like knee joint moments (Browning & Kram, 2007) and greater frontal plane joint moments for both overweight or obese (Gushue et al., 2005; Shultz et al., 2009; Shultz et al., 2014);
- Reduced forward trunk flexion (Sibella et al., 2003; Galli et al., 2000; Gilleard et al., 2002; Gilleard et al., 2008), greater hip extension moments (DeVita & Hortobágyi, 2003; Browning& Kram, 2007; Lai et al., 2008; McMillan et al., 2010), increased hip abduction (Wills, 2004; Ko et al., 2010; Spyropoulos et al., 1991; Lai et al., 2008; McMillan et al., 2010; McMillan et al., 2009; Shultz et al., 2009), smaller knee torque, and lower peak knee flexion angles (DeVita & Hortobagyi, 2003; Foti et al., 2000; Gushue et al., 2005; Ko et al., 2010), and higher peak extended knee moments through initial stance (DeVita & Hortobágyi, 2003; Browning & Kram, 2007; Lerner et al., 2014; McMillan et al., 2010; Gushue et al., 2005; Lelas et al., 2003);
- During level walking, obese adults experience significantly higher peak tibiofemoral contact and greater muscle forces through the gait, thus causing gait alterations (Lerner et al., 2014; Haight et al., 2014; Zeng et al., 2017);

- Diminishing muscle strength with obesity (Cau et al., 2014; Ponta et al., 2014);
- Decreasing plantar flexion angles during stance and swing that is an adaptation to keep a similar speed to that of healthy adults (Spyropoulos et al., 1991; Lai et al., 2008; Browning & Kram, 2007; DeVita & Hortobágyi, 2003);
- Adopted or altered foot structure (Butterworth et al., 2014), so the obese walk with flatter feet (Hills & Parker, 1991), and they have a greater toe out/foot progression angle (Messier et al., 1994; de Souza et al., 2005);
- Reduced peak knee extensor moment scaled to body mass is substantially decreased in obese subjects than in normal-weight individuals (Spyropoulos et al., 1991; DeVita & Hortobágyi, 2003; Lai et al., 2008; Browning & Kram, 2007; Messier, 2010; Runhaar et al., 2011).

1.4.3. Kinetics

Finally, kinetic factors are important because they reveal the significant effect of obesity walking. During walking, obese adults have a greater pelvic obliquity during late stance (Lai et al., 2008; Lerner et al., 2014), as well as increasing torque at the knee joint (Gilleard et al., 2008; Sibella et al., 2003). Leading ligament looseness and muscle strength reduction in ankle joints have been related to excess body weight. Excess body weight is also usually distinguished through lower strength (Hulens et al., 2001).

Increasing power at the knee joint (Ko et al., 2010; DeVita & Hortobágyi, 2003) and greater peak knee extensor moments occur at the knee joint during gait (Silvernail et al., 2013; Ko et al., 2010; Lai et al., 2008; Segal et al., 2009; Russell et al., 2010; Vismara et al., 2007; DeVita & Hortobágyi, 2003). Peak vertical greater absolute GRF (de Castro et al., 2014; Browning & Kram, 2007) and increased vertical GRF have been linked to an increased risk of injury and joint degeneration (Butler et al., 2003). There is also a positive correlation between peak GRF and body mass (Messier, 2010). For example, as body mass increases (greater than 40 kg/m$^2$) people have a smaller number of strides as a result of the reverse link amidst the mean number of steps and BMI. Furthermore, healthy weight subjects have higher peak intensity of physical activity with less exertion than obese subjects (King et al., 2008), reduced impact on proximal leg joints (such as knee joint and hip joint) (DeVita & Hortobágyi, 2003; Ko et al., 2010), reduction in ankle dorsiflexion, higher peak plantar pressure (Butterworth et al., 2014) and greater muscle forces (Lerner et al., 2014; Haight et al., 2014).

Researchers have obtained a great deal of precise knowledge by investigating biomechanical parameters such as gait cycle, time phase, the center of pressure and pace during gait. While aspects of gait have been extensively studied in elderly patients with obesity, examining the centre of pressure would permit a more thorough evaluation of biomechanical parameters, providing more useful and accurate information on the anatomical structures acting in and on the foot during walking. People who are overweight and obese compensate for instability and muscle weakness by changing their walking style, and depend on different body movements to move their excess mass. This study explores the lack of information about functional gait imposed by a small change in body weight. Conversely, a reduction in obesity will lead to improved balance and a lower risk of falling (Aaboe et al., 2011; Song et al., 2015).

Overweight and obesity affect foot function and morphology, and the weight placed on the human foot can play a role in determining both the biomechanical behaviour and the function of the foot (Guiotto et al., 2013). The foot is one of the most complex structures of the human body, comprising multiple active and passive components which provide important support and functionality to the rest of the human body (Richie Jr, 2007). Feet, as the body's base of support, continually withstand GRF through the normal activities of daily living. Several researchers have proposed that the excessive increases in weight-bearing forces caused by obesity, might be damaging to the lower limbs of adults, like the feet (Hills et al., 2002; Wearing et al., 2006). Obesity and overweight have a detrimental impact on the structure and function of the foot, and numerous foot issues and injuries have been connected to defects in the foot (e.g., ulcers in the diabetic foot) that may be caused by excessive loading on a certain part of the plantar surface (Bus et al., 2005).

## 1.5. Plantar pressure measures

Individuals with foot pain have been shown to have altered plantar pressure measures compared to those without foot pain (Mickle et al., 2010). Plantar pressure measures provide a sophisticated way of assessing gait adaptations in those with foot and ankle pathologies (Lobet et al., 2012; McKay et al., 2017). Plantar pressure measures can identify differences in loading patterns and the distribution of pressure acting on the foot during walking (McKay et al., 2017). Both the platform system and insole systems may be utilized to measure plantar pressures, providing high resolution options due to a large number of sensors, thereby providing accurate pressure maps of the foot during gait (Lobet et al., 2012). Plantar pressure analysis provides a reliable method of diagnosing foot and ankle pathologies, including osteoarthritis (Wafai et al., 2015). Additionally, plantar pressure measures have been shown to identify differences across patient groups, particularly for those who frequently fall or are at higher risk of falling (Gray et al., 2014; Moghadam et al., 2011). Not only do plantar pressure analyses provide a way of assessing differences in gait between individuals with ankle osteoarthritis and healthy controls, they also provide a way of assessing the effect of interventions.

The longitudinal arch in the human foot has muscles and ligaments that provide support for maintaining the arch, and these muscles and ligaments mimic the mechanism of an elastic band by storing the energy as they are stretched, and releasing energy as they return to their original state, thus assisting with the propulsion of the body during movement. Increases in body weight affect the ligaments and soft tissue in the arch which lead to a loss of elasticity the arch (Dowling et al., 2001).

A considerable number of research and clinical evaluations have used foot plantar loading assessments because plantar load distribution gives an insight into plantar loading attributes through functional activities like walking and running (Orlin & McPoil, 2000). In addition, studying foot plantar loading is important for the understanding of human foot injury mechanisms, foot biomechanics, foot stress, and the neuropathic foot (Perttunen, 2002; Castro et al., 2013). Plantar pressure assessment can determine loading features on particular plantar zones of the foot (Rosenbaum & Becker, 1997; Chong et al., 2013). In fact, foot plantar load distribution studies are of particular interest as they provide information about the GRF or plantar pressure acting on foot regions, and the physical interactions between the foot and the supporting surface (Orlin & McPoil, 2000). Furthermore, the human foot plays a vital role in the body's kinetic variables/parameters as it serves as a base of support (Mickle et al., 2006; Yan et al., 2013). Finally, plantar foot loading has been extensively observed in both walking (Vereecke et al., 2003; Giacomozzi & Martelli, 2006; Mao et al., 2006; Menz & Morris, 2006) and stationary conditions (Mao et al., 2006).

Scientific clarification on the correlation of increased body mass and the health of the plantar foot is yet to be made. Feet are the only part of the body that are directly connected to the ground during walking. The foot plays a significant role in alleviating the strike coming from the ground while protecting joints from mechanical energy, and it plays an important role in stabilizing and moving the body (Thomas et al., 2011).

Specifically, the longitudinal arch of the foot plays a key role in absorbing and distributing the high ground reaction forces due to its direct influence on such varied aspects as foot function, stability, pain and the predisposition to injury (McCrory et al., 1997; Dowling et al., 2001). Investigation of plantar load distribution allows the diagnosis and analysis of GRFs, or pressures, acting within the foot regions during standing and movement (Menz & Morris, 2006).

A study of human gait involves detailed examinations of various characteristics such as physical and pressure measurement which have been utilized for a better understanding of human gait strategies. In particular, expert analysis that uses various techniques to study human gait analysis and assess abnormal human gait is most frequently based on the pressure measuring system (sensory) or on video recordings (vision) (Prakash et al., 2018). Physical and pressure characteristics are assessed for a better understanding of human gait patterns. A number of techniques are available for analysing gait. These are based on pressure sensors that are placed on the subject’s body, on the floor, or inside the insole of shoes (Alaqtash et al., 2011; Muro-de-la Herran et al., 2014). Pressure sensors are used to obtain the kinetics of the subject’s movement and are being divided into two types: force platforms and pressure systems (Robertson et al., 2013). Both systems are used by clinicians and researchers and rely on quantifying the centre of pressure of various foot regions (Wearing et al., 2012; Cousins et al., 2013). They provide information about the foot; its structure and plantar loading characteristics when standing, as well as during gait (Mathieson et al., 1999; Tong & Kong, 2013). They may also be based on a video camera to capture human body movement by placing direct or indirect markers on the subject’s body (Lee et al., 2014).

Several authors have investigated the functioning of feet using pressure sensors. They selected different parameters in their trials: different numbers of regions of the foot (from two to ten), age group, weight, and variables that are used to describe plantar pressure loading including peak pressure (PP), peak force (PF), pressure time (PT), pressure time integral (PTI), centre of pressure (COP) and centre of mass (COM) (Cousins et al., 2012; Cousins et al., 2013; Butterworth et al., 2015; Song et al., 2015). This research indicates the useful contribution of pressure sensors in providing insights into foot function and foot structure.

The most important technique used to study gait in this work is the in-shoe pressure F-Scan© (Tekscan) which can provide valuable clinical information about the management of individuals at risk of developing flat foot, foot ulcerations or Charcot foot by providing information about their footprint (Riddiford-Harland et al., 2011; Periyasamy et al., 2012). Therefore, in-shoe pressure F-Scan© (Tekscan) is the most important technique utilized to study gait in this work. The goal of this work is to provide a more accurate picture of one aspect of the diverse effects of simulated body weight, and to examine its connection to plantar pressure patterns in light of socio-demographic data.

## 1.6. Research gap

With the increased prevalence of overweight and obesity in adults, it is essential that further work be conducted to assess the full effect of various adult weight categories on the foot by evaluating plantar pressure patterns. The plantar pressure patterns will be analysed considering age and BMI, to provide a more comprehensive understanding of the connection between simulated body weight and the insole system. Therefore, this study focuses on investigating the plantar loading differences between groups of adults aged 24 to 50 years.

## 1.7. Research aim

The aim of this study is to investigate the effect of body weight on the feet and to investigate the use of simulated body mass to study the effect of variable body mass on the foot plantar in adults aged 24 to 50 years of age, while walking at a self-selected pace.

## 1.8. Research objectives

To achieve the overall aim of this research, the following objectives were defined as:

1. Assessing dynamic foot plantar pressure characteristics in adults who are normal weight, overweight or obese during level walking using the insole pressure system, and comparing these values (the findings) with those of a healthy control group;
2. Studying the impact of simulated body weight (SBW), used to increase the weight from healthy to overweight and obese, by comparing higher body weight which simulated body weight (SBW) (by wearing a vest with 10, 20, and 30 kg weight) group with the normal body weight (NBW, 0 kg);
3. Evaluating the spatial relationship between the trace of the centroid of the area of contact with a heel strike, midstance, and toe-off phases of simulated body weight (SBW) groups, using the in-shoe plantar pressure system.

## 1.9. Research questions

The research questions were:

1. Are there any noticeable changes in plantar pressure load between healthy, overweight and obese adults?
2. How do changes in weight (simulated body weight) influence plantar pressure patterns?
3. What is the most suitable plantar pressure data to provide an understanding of the relationship between simulated BMIs and gait characteristics such as force, contact area, contact pressure, plantar pressure integrals, and peak pressure measures?
4. What are the spatial correlations between the trace of the centroid of the area of contact of the plantar surface and the trace of the center of pressure captured by the pressure mat during gait respectively?

## 1.10. Significance of the research

Completing this research may bring a number of important benefits. These are:

1. Understanding how body weight changes pressure/force distribution and plantar surface during gait;
2. Understanding how simulated body weight changes the dynamic data of foot pressure;
3. Evaluating the innovative techniques used at USQ in: (a) the determination of the change of x and y locations at various incidence angles of plantar pressure data; and (b) the detection impact of increasing body weight on plantar pressure measurements namely pressure time integral, peak pressure, pressure contact area and average pressure.

## 1.11. Thesis structure

A brief outline of each chapter is given below:

After the current chapter, a literature review is presented in **Chapter 2**, introducing the background which concentrates on the prevalence of overweight and obesity as well as the causes and consequences of overweight and obesity, and reviews human gait analysis. The anatomy of the human foot and the main sections of the foot connected to the problems, are also considered, as are plantar load and pressure measurement techniques. **Chapter 3** focuses on the practical aspects of the three experiments and their corresponding methodologies to extract the body weight on gait. The results and discussion for the first experiment which relates to objective one are provided in **Chapter 4,** which proposes a definition of obese adults compared with overweight and healthy individuals**. Chapter 5** presents the integrated discussion for the second experiment, which relates to objective two and provides an explanation for the simulated body weight, and the effect on plantar foot measures. **Chapter 6** focuses on the results and discussion for the third experiment, which relates to third objective on enhancing the x-axis and y-axis with coordinate values that represent simulated body weight with to three significant stages of the load phase: 1) heel strike; 2) midstance; and 3) toe-off, for both feet. The conclusion, presented in **Chapter 7,** brings together all the chapters. It summarizes the main findings from the experiments together with suggestions for future work.

# 2. LITERATURE REVIEW

## 2.1. Introduction

The literature review is presented in the following order: Section one reviews overweight and obesity, Section two considers human gait, Section three discusses the human foot, Section four considers plantar pressure and Section five explores pressure measurement. The literature review then concludes with a brief discussion and summary.

## 2.2. Overweight and obesity

During the past ten years, the prevalence of overweight and obesity has been increasing rapidly worldwide. Moreover, it has become more common, not only in adults, but also in adolescents and children (Zimmet et al., 2014). Overweight and obese adults have become significant public health concerns worldwide (Sheffler et al., 2014). In 2016, the World Health Organization (WHO) indicated that, from a global perspective, nearly two billion (aged 18 years and older) of the population are considered overweight and, of these, over 650 million are clinically obese. Thirty-nine percent of people aged eighteen years and over have been found to be overweight; thirteen percent were obese. More disturbingly, obesity is on the rise. The worldwide prevalence of overweight or obese males has increased from 28.8 to 36.9% between 1980 and 2013, whilst that of females rose from 29.8% to 38.2% during the same period. This means the rate of obesity has quadrupled in adults and doubled in children in the past 30 years (Ogden et al., 2014).

The prevalence of obesity has increased dramatically over the past three decades in virtually every country. **Figure 2.1** illustrates the global epidemiology of obesity in adult males. According to the Centre for Disease Control and Prevention, in the United States alone, there are more than 78.6 million obese adults (CDC, 2014). Currently, in the United States, approximately 33.9% and 38% of American adults are overweight and obese, respectively (Fryar et al., 2014). Alarmingly, American obesity rates have nearly doubled for adults and tripled in children since the 1980s (Obesity Rates & Trends Overview, 2015). In Australia, data from a recent Australian Institute of Health and Welfare report shows the problem has escalated to the point where nearly two-thirds (63%) of adults are overweight and/or obese (of both sexes) with 28% categorised as obese, and more than one in four children are also considered to be obese (Abo, 2015).

Being obese presents higher health risks than being overweight (AIHW, 2016; Australian Government, 2017), but both present potential health problems. The obese population has a higher risk of suffering ulcers because of extra pressure in the vascular system (Firat, 2017). Obesity and diabetes are associated with each other in that, and obesity plays a significant role in the cause of diabetes (Leong & Wilding, 1999). Obese people have extra adipose tissue, and the existence of adipose tissue increases the pressure and pain sensitivity threshold. Some studies determined that high plantar pressure was related to obesity and that plantar pressure was related to plantar sensitivity (Wu & Madigan, 2014). Plantar pressure is frequently measured to solve foot problems in patients with pain, diabetes, or rheumatism (Lee et al., 1996). The increased contact area was not found to be sufficient to compensate for the high forces generated during walking, which cause higher plantar pressures with increased stress (Mickle et al., 2006). Therefore, obese individuals feel less pain when a force, such as pricking with a needle on their forearm, is applied (Scheinfeld, 2004). Feeling less pain and sensitivity causes pressure ulcers. It can be seen also in elderly people for the same reason, and in diabetics whose disease is a consequence of obesity.

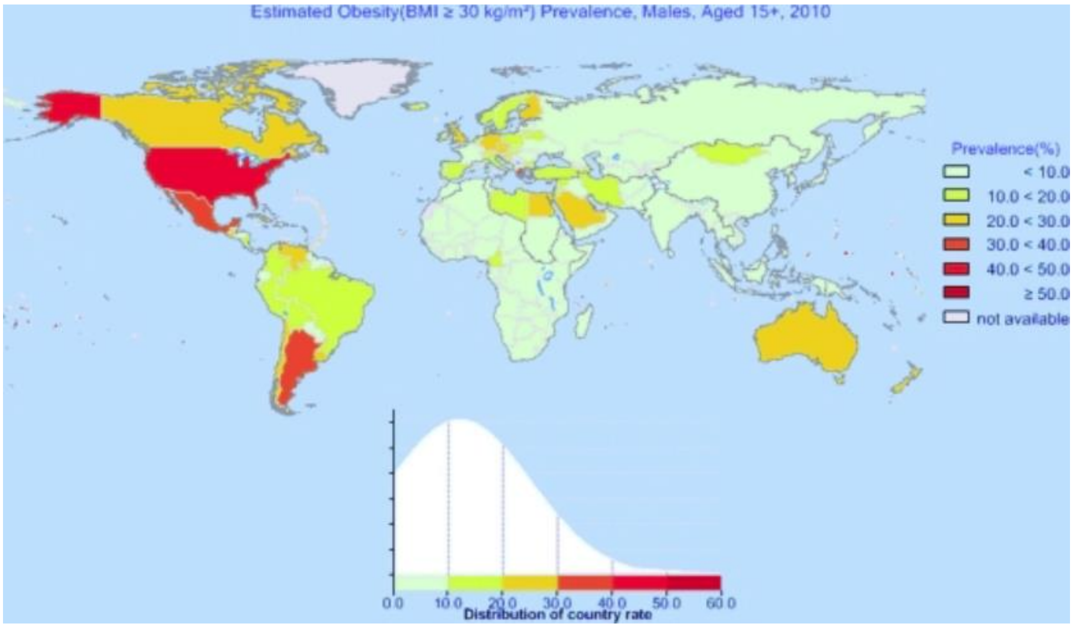



**Figure 2.1.** Prevalence of obesity worldwide in males 15 to 100 years old in 2010. This figure represents the prevalence of obesity (BMI > 30 $kg/m^2$) among males on a global scale in the year 2010 (Haidar & Cosman, 2011)

The significant physiological and biomechanical complications related to overweight and obesity have generated substantial economic costs because both conditions are serious, complex, and may be lifelong. One aspect of these cost is that the diseases associated with overweight and obesity place a major burden on the economy through an increased use of the health care system and treatment costs. Other aspects will be mentioned below. In 2014, the global economic impact from obesity was approximately $2.0 trillion, or 2.8% of the global gross domestic product, roughly equivalent to the global impact of smoking or armed violence, war, or terrorism (Dobbs et al., 2014). In the United States, approximately $147 billion per year is used up on obesity-connected health care costs (CDC, 2011). In Australia, the total cost of obesity to society and governments has been estimated at $58 billion (in 2011-2012), which includes a direct cost of $8.6 billion for productivity costs due to short and long-term employment impact $3.6 billion, health system costs of $2 billion and carer costs of $1.9 billion. In addition, lost wellbeing disability and the early death consequence of obesity and its effects cost the country $49.9 billion (AIHW, 2017). Therefore, overweight and obesity were the second highest contributors to the burden of disease in Australia (Sainsbury & Zhang, 2012).

# CHAPTER 2: LITERATURE REVIEW

Prevalence of foot pain and pathology can be disabling, leading to more complex orthopaedic complaints overtime. Foot pain contributes to 20% of hospital orthopaedic referrals and surgical procedures (Chuckpaiwong et al., 2009), with a larger proportion (24-41%) of the population suffering from foot pathology (Riskowski et al., 2011). Pathologies of the foot have been associated with many different causes including obesity, foot mechanics, foot posture, diabetes and reduced range of motion within the foot (Chuckpaiwong et al., 2009). Pain due to ankle osteoarthritis tends to be aggravated by weight-bearing activities, such as walking, climbing stairs and jogging (Valderrabano et al., 2007). Hill et al. (2008) examined 3,206 participants and found that obese cases had an increased prevalence of foot pain. Individuals with foot pain have been shown to have altered plantar pressure measures compared to those without foot pain (Mickle et al., 2010).

Overweight and obese people are experiencing more foot pathologies (such as plantar fasciitis, plantar heel pain) due to increased body weight than they did in the past (Riddle et al., 2003; Irving et al., 2007; Prichasuk, 1994). Some research studies have found that there is a clear association between foot pain and elevated plantar pressure for overweight and obese adults during gait. It has been demonstrated that load carriage can adversely affect a number of physiological parameters such as gait (Birrell & Haslam, 2009, 2010; LaFiandra et al., 2003; Smith et al., 2006). So far, some research studies in western countries have revealed that plantar pressure is increased in obese adults (Gravante et al., 2003; Hills et al., 2002; Birtane & Tuna, 2004). It is estimated that two million people around the world present with chronic plantar heel pain each year, of which the number one cause is plantar fasciitis (Thing et al., 2012). Also, the prevalence of arthritis in American normal weight adults over forty years of age is between 25.7 and 33%, while in obese adults the prevalence is between 37.0 and 44.4% (Ong et al., 2013). In addition, one of the most common presentations of foot pain in clinical practice is pain in the plantar heel. Pain related to the pathology of the plantar fascia is the most commonly diagnosed pain. Preventive examinations prove that insufficient quality or quantity of increased weight may initiate functional or structural modifications of the foot that may cause pain for the patient. Foot pain occurs relatively often. Approximately 3.6% South Australian suffer from heel pain because of increased body weight, according to the North West Adelaide Health Study, which shows a similar prevalence to data for the United States (7.3%) and the United Kingdom (9.8%) (Garrow et al., 2004; Riddle & Schappert, 2004; Hill et al., 2008; Dufour et al., 2009).

### 2.2.1. Definition and classification for overweight and obese adults

Overweight is defined as a state of weighing more than healthy body weight, thus being at risk of developing obesity. This means that the weight exceeds the threshold of criterion standard or reference value BMI greater than 24.5 kg/m$^2$ (Fallon et al., 2005). Obesity is defined as having too much or abnormal or excessive fat accumulation of body fat adipose tissue and can be associated with serious medical complications that impair quality of life. Therefore, overweight and obesity are not synonymous terms (Kopelman, 2000; Fallon et al., 2005). Both terms thus imply that a person's weight is higher than the healthy level for his or her height. A human can be overweight, but not obese through having extra muscle or bone (Fallon et al., 2005). Both conditions are caused by the energy imbalance between calories consumed and calories expended (Sheehan & Gormley, 2013). Healthcare experts have commonly utilised the BMI in the adult population to classify and define the body state as underweight, healthy, overweight and obese (Rossouw et al., 2012). BMI (kg/m$^2$) is calculated by dividing the ratio of body weight (in kilograms) by the square of the height value (length) in metres of an individual (Jegede et al., 2017; Vijayakumar et al., 2016) as described in **Equation 3.1. Chapter 3, Section 3.3.3.5.**

According to this system, people with a BMI of less than 18.5 kg/m$^2$ are considered by the WHO to be underweight. A healthy or normal weight range is 18.5 to 24.9 kg/m$^2$ while 25.0 to 29.9 kg/m$^2$ is considered to be overweight or pre-obese. Over 29.9 kg/m$^2$ is obese. The obese classification can be further split into three categories, Class I is from 30 to 35 kg/m$^2$, Class II is from 35 to 40 kg/m$^2$, Class III or morbidly obese is over 40 kg/m$^2$ (WHO, 2016). BMI is an indicator for assessing overweight and obesity in a population since it can be applied to all categories of people. BMI is a useful and simple index which has a clear connection to the amount of fat mass (WHO, 2016). In general, a person with the BMI greater than or equal to 30 is classified as obese (WHO, 2016).

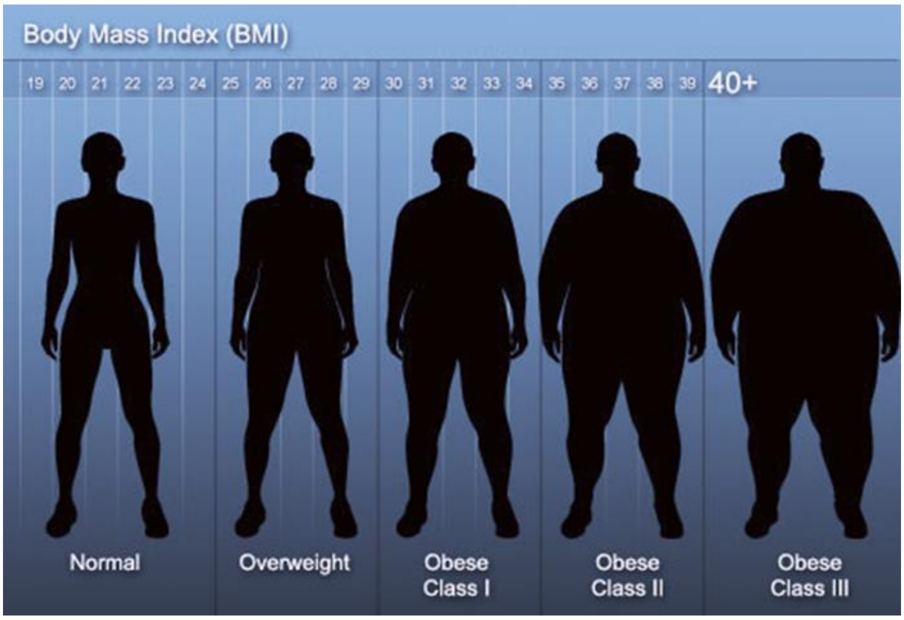



**Figure 2.2.** Classification of BMIs human body requirements for each group (from CDC, 2014)

### 2.2.2. Causes of overweight and obesity

Reasons for increasing incidences from illnesses relating to overweight and obesity are not singular but include a wide range of influences. For instance, unhealthy food, quantity of food consumed; meaning an imbalance between energy intake and energy expenditure, insufficient physical activity, gender, environmental factors, illness, medication, psychological factors, and genetics play a role in this accumulation of excess body fat (Wearing et al., 2006; McAllister et al., 2009; WHO, 2011; Hageman et al., 2013; Zimmet et al., 2014).

### 2.2.3. Consequences of obesity and overweight on health

Both overweight and obesity have been recognised as crucial health problems (outcomes). Several health complications are associated with overweight and obesity. For example, it has been identified as the leading cause of Type II diabetes mellitus. Also, people who are obese are more likely to suffer from coronary heart disease, dyslipidemia (for example, high total cholesterol or high levels of triglycerides), hypertension (high blood pressure) and cancers (endometrial, breast, and colon).

Furthermore, people with obesity have higher rates of osteoarthritis (a degeneration of cartilage and its underlying bone within a joint for hip, knee, and ankle), poor physical functioning, and functional gait abnormalities (Birtane & Tuna, 2004; Kushner & Roth, 2003; Lyytinen et al., 2014; Russell & Hamill, 2011; Lee & Kean, 2012; WHO, 2016). In addition, obesity has a sturdy connection with lower extremity disorders, like osteoarthritis and pain in both ankle and foot (Frey & Zamora, 2007, Ozdemir et al., 2005). For instance, a recent systematic review investigating twenty-five studies involving 93,224 participants in the general population, have noted that there is a strong relation to non-specific foot pain and chronic plantar heel pain and obesity (Butterworth et al., 2012). Obesity modifies body geometry. It increases the mass of the different segments, and imposes functional limitations, primarily affecting the lower limbs (Kortt & Baldry, 2002), which can significantly influence the biomechanics of activities during daily living predisposing obese individuals to injury (Wearing et al., 2006).

An increasing number of deaths can be attributed to these conditions (Perju-Dumbrava et al., 2017). To summarise, various health conditions connected to excessive weight gain, relate to both overweight and obesity, such as Type II diabetes mellitus and poor physical functioning. Similarly, it is reported that obesity and an increase in weight in children and adults were related to musculoskeletal pain, especially involving the lower extremities (knee, feet, and hip), which leads to disability (Stovitz et al., 2008).

As mentioned above, obesity is associated with musculoskeletal problems, higher rates of hyperuricemia, and immobilisation due to pain in the lower back and knees, gout, and in the feet (Birtane & Tuna, 2004; Kushner & Roth, 2003; Lai et al., 2008; Lyytinen et al., 2014).

In addition, overweight or obesity causes several morphology physiological changes, including the adaptation and impairment of the musculoskeletal structure and function in adults because of excess body weight (Bankoff et al., 2003). Such as abnormalities of the foot associated with a different way of walking; and the abnormal gait that may eventually lead to falls (Pan et al., 2016). In addition, excess weight negatively affects the joints of the lower limbs like hips, knees, ankles and feet, which can cause their misalignment due to increased stress on joints (Bankoff et al., 2003; CDC, 201; de Sá Pinto, 2006), and metatarsalgia related to pain and inflammation in the ball of the foot (Chang et al., 2012), limitations in muscle strength, decreased mobility, and altered positioning of the feet, all of which affects posture (Horak, 2006; Lyytinen et al., 2013).

Obesity also results in an increase in the ground contact area of the feet, altering the plantar pressure distribution and inducing pressure peaks in certain parts of the foot (Lee, 2009, Dowling et al., 2001). Peak plantar pressure is the highest pressure registered on each part of the foot, and its evaluation provides a strong clinical tool for understanding the structural and functional consequences of obesity (Filippin et al., 2007). The most negative consequences of being overweight or obese are that individuals often exhibit greater posture deficits (Gilleard & Smith, 2007; Greve et al., 2007) and gait alterations (Ko et al., 2010; Segal et al., 2009; Lai et al., 2008).

There is also likely to be an effect on balance control (Greve et al., 2007; Singh et al., 2009) and as a result, people suffering from obesity also have an increased risk of falling (Corbeil et al., 2001) as well as an increased likelihood of foot ulceration (Vela et al., 1998) and heel pain (Prichasuk, 1994). It has also been reported that impairments caused by overweight and obesity may include atrophied leg muscles, longitudinal arch and plantar fat pad, development of claw toes and hammer toes and limited joint mobility (Butterworth et al., 2012).

Numerous researchers have established that obesity affects walking patterns in negative ways because of the impact of carrying additional fat mass. This impact, together with reduced relative muscle strength, has been associated with a progressive worsening of health and increasing discomfort (Lai et al., 2008; Sheehan & Gormley, 2013). Therefore, to undertake human gait analysis, three major groups of gait parameters should be considered. The most common types of parameters researched in gait analysis are spatiotemporal, kinematic, and kinetic parameters (Winter, 2005). From these parameters, several types of knowledge about any person can be extracted (Collins et al., 2002). The following sections discuss different gait analysis components.

An increasing body of evidence has shown obesity to have a negative effect on the development, treatment, and outcome of lower extremity pathologic entities, including diabetic foot disease (Pirozzi et al., 2014). But, obesity, in particular, has been associated with numerous serious and chronic health conditions, which may have negative physiological and mechanical implications on the body. For example, Type II diabetes mellitus, coronary heart disease, metabolic syndrome, dyslipidemia (for example, high total cholesterol or high levels of triglycerides), hypertension (high blood pressure), inflammation, cancers (kidney, endometrial, colorectal and pancreatic prostate, breast and ovarian, and colon), stroke, sleep apnoea and cardiovascular diseases (Reeves et al., 2007; McClean et al., 2008; Guh et al., 2009; Bell et al., 2014; CDC, 2015; WHO, 2016; AIHW, 2017). Obesity also presents a greater risk for bone and joint problems, such as osteoarthritis (a degeneration of cartilage and its underlying bone within a joint for hip, knee, and ankle). Due to obesity, excessive and cumulative joint loads have been suggested as posing a high risk for the onset and progression of osteoarthritis (CDC, 2011; Jiang et al., 2012; Mezhov et al., 2014). Obesity has been reported as having a direct link to neuro-musculoskeletal deficiencies (Dario et al., 2015; Singh et al., 2015), poor physical functioning, and functional gait abnormalities (Russell & Hamill, 2011; Lee & Kean, 2012; WHO, 2016). Overweight and obesity conditions can be attributed to increasing number of deaths (Perju-Dumbrava et al., 2017).

Limitations in muscle strength are associated with limited mobility, which can adversely affect the quality of life (Stenholm et al., 2009; Vincent et al., 2010) and decreased mobility. The risk of falls is twice as common among obese individuals compared to healthy weight individuals (27-15%) (Hahn et al., 2018). Postural instability goes hand in hand with an increased risk of falling and related injuries (HitaContreras et al., 2013) and altered positioning of the feet (Horak, 2006; Lyytinen et al., 2013). Overweight and obese individuals with foot pain show a higher level of heel-pad thickness and less heel-pad elasticity which may, lead to a decreased level of shock absorption and cushion (Prichasuk et al., 1994). The time to achieve peak pressure and peak pressures in the metatarsal heads were higher pressure rate or time to pressure is used to estimate the risk of injury in the plantar portion of the foot (Yan et al., 2013). Higher pressure indicates a greater impact on the foot, and a higher risk of injury (Yan et al., 2013).

The most negative consequences of being overweight or obese are that individuals often exhibit greater posture deficits (Gilleard & Smith, 2007; Greve et al., 2007) and gait alterations (Ko et al., 2010; Segal et al., 2009; Lai et al., 2008). There is likely to be an effect on balance control (Greve et al., 2007; Singh et al., 2009) and as a result, an increased risk of falling (Corbeil et al., 2001) as well as an increase in the likelihood of foot ulceration (Vela et al., 1998) and heel pain (Prichasuk, 1994). It is reported that the impairments often include atrophied leg muscles, longitudinal arch and plantar fat pad, development of claw toes and hammer toes and limited joint mobility (Butterworth et al., 2012). These structural and functional abnormalities of the foot are associated with a changed walk strategy, eventually leading to falls (Pan et al., 2016). Overweight or obese individuals often exhibit greater impairments in posture and gait and have an increased risk of falling.

Several researchers have established that obesity affects gait patterns in adverse ways because of the impact of carrying additional fat mass. This impact, together with reduced relative muscle strength, has been associated with a progressive worsening of health and increasing discomfort. One of the important causes of impaired physical function in obese individuals is believed to be reduced muscle strength (Stenholm et al., 2009) and lowered skeletal muscle mass (Zoico et al., 2004, Bosy-Westphal et al., 2015). Stenholm et al. (2009) reported that those older obese individuals with decreased lower limb muscle strength had a higher risk for the development of physical function disability compared with those of a healthy weight. Zoico et al. (2004) demonstrated that a low percentage of muscle mass significantly increased the probability of experiencing functional limitations. Sibella et al. (2003) determined that, in completing a sit-to-stand task, obese subjects adopted a different movement strategy from non-obese subjects. The obese subjects' forward trunk flexion was reduced, and their feet moved backwards from the initial position. Sibella et al. (2003) suggested that the reduction in trunk flexion represented an attempt to diminish loading of their lower back. The next section describes some fundamental gait concepts and introduces human gait.

## 2.3. Human foot anatomy

Foot and ankle movement are critical for human locomotion. They attenuate impact forces, provide support and stability for the body by interacting with the supporting surface and assist forward progression (Stefanyshyn & Nigg, 1997; Whittle, 1999). To enable walking, each of these functions relies on a complex series of coordinated joint motions (Lundgren et al., 2008). The foot is the link between the supporting surface and the lower extremity during walking. The foot, as the most distal part of the lower limb chain, is in contact with the ground and resists the forces that pass through it (Ledoux & Hillstrom, 2002). Abnormal pressure distribution on the plantar surface of the foot may cause pain and act as a source of pain (Becker et al., 1997). Such pain can be more prominent as a result of obesity where the centre of pressure constantly changes because of the persons increased body weight (Periyasamy et al., 2012; Yan et al., 2013). This illustrates that understanding foot biomechanics helps clinicians to more effectively evaluate normal and abnormal conditions (Kirby, 2000).

The foot is a major part of the skeleton that bears significant loads during locomotion (Periyasamy et al., 2012). In addition, it is considered one of our most distinctive morphological and functional features. The foot is one of the most complex musculoskeletal structures of the human body (Ganea et al., 2017). It consists of twenty-six bones and thirty-three joints (twenty of them active joints), layered with an intertwining web of more than hundred muscles, ligaments, cartilages, and tendons. It contains a network of blood vessels, nerves, skin, and soft tissue, such as the plantar fascia or plantar fat pad as shown in (**Figure 2.3)**.


**Figure 2.3.** The foot connects with the lower leg at the talus, tibia, and fibula interface (Lochner, 2013)

In fact, the only part in contact with the ground through standing and movement is the foot. Generally various features of the foot structure is accompanied via changing plantar pressure distribution and situations of the lower extremity bones, muscles, tendons and ligaments, which in turn, influence lower limb biomechanical features and foot function (Cavanagh et al., 1997). Understanding both structure and function characteristics of the foot might assist recognition of the aetiology of a number of lower extremity defects. Excess body weight causes detrimental alterations of the foot structure and function, which is a potential exegesis to the association of obesity with ankle and foot defects (Butterworth et al., 2015).

Flexible foot structures work in unison to serve a variety of biomechanical functions. These structures allow the human foot to support weight, absorb the shock of impact force, serve as levers to propel the leg forward, and are responsible for maintaining body balance in statics and dynamics through symmetrical distribution of plantar pressure (Hicks, 1954; Hamilton, 1967; Elftman, 1969; Netter & Colacino, 1989; Putz & Pabst, 2006; Abdul Razak et al., 2012; Ganea et al., 2017).

Structurally, the main sections of the human foot can be divided into three main sections: the rearfoot, midfoot, and forefoot **(Figure 2.4).** This presents the way the human foot is connected to the body via the articulating surfaces provided by the tibia and fibula (Lochner, 2013).

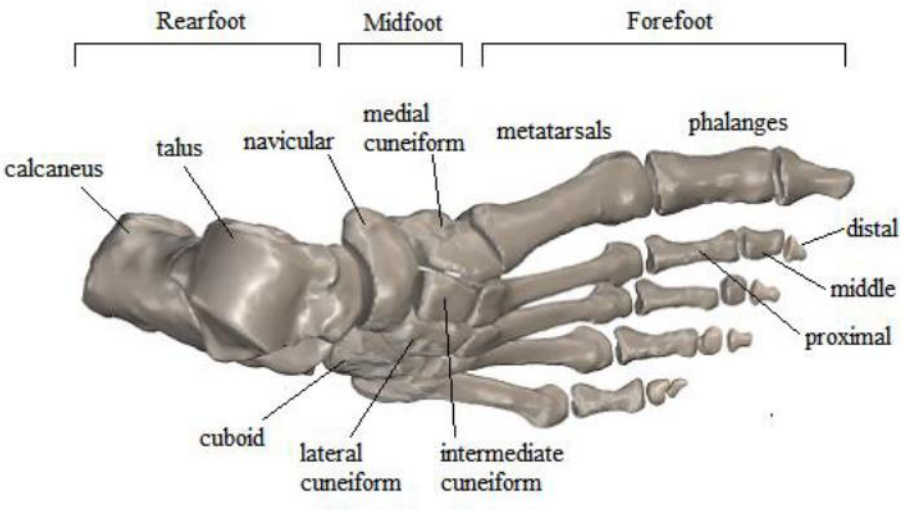



**Figure 2.4.** View of the dorsal bones of the rearfoot, midfoot, and forefoot (adapted from (Oatis, 2009)

The foot plantar fat pad is organised into two layers of adipose and connective tissue that provides cushioning to the underlying foot structures (Hills et al., 2002). The function of the plantar fat pad is to absorb shock loading, particularly on the forefoot and heel regions (Ozdemir et al., 2004; Natali et al., 2010). The plantar fat pad is one of the main risk factors of developing foot pathologies like diabetic foot ulceration in both adults and children (Patry et al., 2013; Yan et al., 2013). Common in people suffering simultaneously with obesity and diabetes, is a foot ulcer; a state of skin erosion characterised by the inability to self-repair (Levin & O'Neal, 1988).

#### 2.3.1. Foot type

Foot and ankle disorders have been reported in several studies, which show that they are positively associated with obesity (Butterworth et al., 2013; Butterworth et al., 2012). Moreover, research has shown that obese adults have a greater prevalence of foot and ankle disorders compared to both normal-weight adults and overweight adults (Krul et al., 2009). Explaining the potential exegesis for the connection of obesity to foot and ankle defects, is that increasing body weight causes mischievous changes to the foot structure and function (Butterworth et al., 2015). In addition, the foot structure and arch play key roles in optimal personal wellbeing (Fukano & Fukubayashi, 2009).

Because the medial longitudinal arch is the primary shock absorbing structure of the foot, this area of the foot is particularly important for foot function (Oatis, 2004). Moreover, the medial longitudinal arch not only absorbs, but also dissipates high ground reaction forces or pressures that are generated during activities of daily living. Although this arch comprises bony articulations as well as ligaments and muscles, it is primarily the ligaments that support and stabilise the longitudinal arch (Jahss, 1982; Ker et al., 1987). They also act as powerful stores of mechanical energy, thereby decreasing peak joint loads and increasing efficiency (Ker et al., 1987). Additionally, they prevent compression of the plantar regions of the foot that house muscles, nerves, and blood vessels (Jahss, 1982; Abboud, 2002). It has been reported that the impairments caused by overweight and obesity often include atrophied leg muscles, longitudinal arch and plantar fat pad, the development of claw toes and hammer toes, and limited joint movement (Butterworth et al., 2012). These structural and functional abnormalities of the foot are associated with altered ways of walking (Pan et al., 2016). However, over time, excessive body weight is characterized by increased vertical forces which may lead to reduced muscle strength and may stretch ligaments beyond their elastic limit, damaging soft tissues and increasing the risk of foot discomfort and subsequent development of foot pathologies (Dowling et al., 2001).

As mentioned above, dissipating plantar pressure distribution is also affected by foot type. Typically, the foot structure is described and classified according to foot type. There are three various categories based on the height of the foot arch (medial longitudinal). These are high foot arch (pes cavus), normal foot arch and low foot arch or flatfoot (pes planus) as presented in **(Figure 2.5)**. Arch type is typically discussed specifically in relation to the medial longitudinal arch.

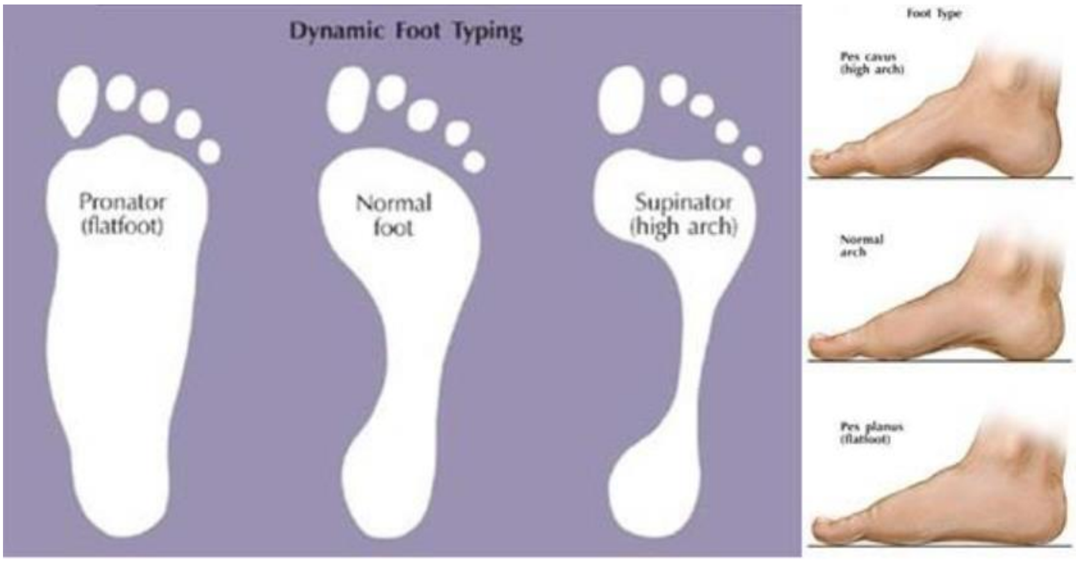



**Figure 2.5.** Three different types of human foot arch and the contact area of each type (Kraushaar, 2005)

Load distribution on the foot is also affected by foot type. For example, previous literature has shown that the applied pressure underneath the plantar perfunctory of the flatfoot increases through foot movement, especially within the rearfoot, medial midfoot and lateral midfoot as compared with the normal foot (Queen et al., 2009). Contact area (CA) and peak pressure (PP) in midfoot noticeably decreases in individuals who have a high foot arch (cavus foot) (Queen et al., 2009).

Chuckpaiwong et al. (2008) studied the correlation between foot shape and the risk of plantar injuries and found that during foot movement, the stress and the PP concentrated on the fifth metatarsal of individuals with normal and high foot arch, whereas PP increased in the second and third metatarsal of the flat foot.

Plantar pressure measurements can be affected by both foot type and foot deformities. Using an Emed-SF® system, Burns et al. (2005) studied thirty subjects with idiopathic cavus foot; ten with neurogenic cavus foot and thirty with normal feet. The pressure time integrals in the rear foot and forefoot in both cavus foot groups were higher than in the normal group. Other studies have shown that subjects with hallux valgus, toe deformities, diabetes with neuropathy, leprosy and rheumatoid arthritis can display altered plantar pressure in the forefoot (Bus et al., 2005; Slim et al., 2012; Mickle et al., 2011; Gurney et al., 2008).

Accordingly, subjects with other forefoot complaints such as bunions, hammertoes, plantar plate pathology, systemic arthritis and diabetes have not been included in the current research project. Data were collected on both feet for ten healthy participants using the Emed®. Six measurements were demonstrated to be reliable with intra-class correlation coefficients (ICC) greater than 0.8 (Zammit et al., 2010).

## 2.4. Human gait analysis

The gait can be known as walking; a procedure of movement that uses both legs alternately and provides together propulsion and support (Whittle, 2007). In general, gait analysis assistance is used to study various kinds of movement patterns as well as forces involved in producing those movements and permits measurement and interpretation of kinematics and kinetics (Switaj & Connor, 2008). Human gait analysis is the examination of a person's style of gait, which is a term applied to the movement of human limbs through locomotion. As one researcher explains, human gait analysis is the methodical study of human locomotion (Chakravarthy et al., 2017). Gait is integral to the way of human movement and includes walking, running and crawling (Nutt et al., 1993). Based on the review of section 2.3 on the human foot, human gait can provide a wide variety of information that can be utilised in the study of various aspects of health such as biometrics, disease diagnosis, load determination and injury rehabilitation (Boulgouris et al., 2005; Piecha, 2008; BenAbdelkader & Davis, 2002; Hailey & Tomie, 2000).

Examination of the human walk has been used in diverse areas, such as physiotherapy, the identification of people (Muro-De-La-Herran et al., 2014) and security (Nair & Kendricks, 2016). Physiotherapy analyses gait limitations caused by sports activities and musculoskeletal and neurological diseases, such as Parkinson's disease (Hannink et al., 2017). Physiotherapists analyse gait patterns to recognise normal and pathological gait movements (Vieira et al., 2017). Moreover, gait analysis, which is linked to human walking, has been undertaken by researchers. Gait analysis methods are used for observing negative deviations in the gait features, as well as determining their reason and influences (Johnson & Bobick 2001; Prakash et al., 2015). Moreover, gait analysis has been established as the clinical technique for determining gait disabilities and dynamic position and coordination during movement (Kavanagh & Menz, 2008). It can be a useful tool as it provides quantitative information about personal gait to help in the provision of optimal treatments (Kadaba et al., 1989; Simon, 2004). Gait analysis assists therapists, physicians, biomechanics and other experts as well as researchers. All information is used to assist the patient once they have undergone measurement of joint kinematics and kinetics, such as lower limb rotations, knee movement and foot placement (Agrawal et al., 2007; Yakimovich et al., 2006; Pollo et al., 2002). Gait analysis is an important tool in defining the biomechanical factors that may affect the progression of certain pathologic conditions, like shaking, rigidity, etc. and describes the internal and external forces acting on the stability of human movement (Duarte & Freitas, 2010; Chang et al., 2004; Miyazaki et al., 2002; Lynn et al., 2007). The goal of gait analysis is to identify gait phases, which may be seen in each normal gait cycle of human walking patterns and can thus be analysed (Miyazaki et al., 2002; Lynn et al., 2007). Gait analysis has been the most studied topic for assessing the locomotor characteristics of humans.

### 2.4.1. Human gait cycle and phases

The gait cycle consists of two periods of double support and two periods of single support. The double support phase is the period during which both feet are on the ground. The stance and swing phases or single support phase, typically make up the main phase sequence of this repetitious cycle by two limbs. The gait cycle starts with the first contact of one foot and ends at the next contact of the same foot. Each normal gait cycle of human walking patterns consists of two main phases, the stance phase and the swing phase (Miyazaki et al., 2002; Lynn et al., 2007). The term 'human gait' denotes locomotion or manner of moving on human feet (Perry & Davids, 1992). It involves two major phases, stance and swing **(Figure 2.6)** (Perttunen, 2002). The stance phase represents the foot-surface interaction with the supporting surface and can be divided into three stages: 1) an initial double limb stance/heel strike; 2) single limb stance/midstance, 3) terminal double limb stance/toe-off (Perry & Davids, 1992; Perttunen, 2002).

The double limb stance period occupies approximately 10% of the complete gait cycle. The single limb stance occurs from 10% to 30% of the cycle and represents the clinically important phase of the gait cycle. The terminal double limb stance or toe-off occurs from 40% to 60% of the period of the gait cycle (Cuccurullo, 2004).

The stance phase includes two periods of double support and one single support. The stance phase accounts for approximately 60% of a single gait cycle. The first phase is the stance, which begins at initial foot contact and refers to the entire time the foot is on the ground. This means that the stance phase starts at heel touchdown and ends at toe-off for the same foot, as shown in **(Figure 2.6)**. The stance phase includes five sub-phases: initial contact, loading response, mid-stance, terminal stance, and pre-swing (Ayyappa, 1997). Pre-swing has been called double support and occupies approximately 10% of the cycle. Right after toe-off, there is a period of single support when just one foot is on the ground. The second phase is the swing phase, which begins with the foot lifting off the ground. The single gait cycle accounts for approximately 40% (Winter, 2009). It denotes the time that the foot is in the air advancing forward (Miyazaki et al., 2002; Lynn et al., 2007).

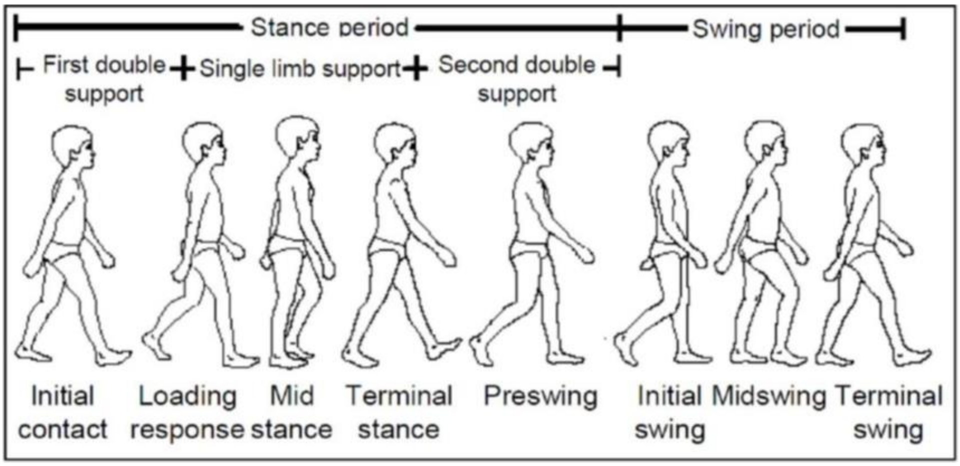



**Figure 2.6.** The normal gait cycle of an 8-year old boy (Perttunen, 2002)

Perttunen (2002) reported the period of the stance phase takes approximately 60% of the gait cycle, while the swing phase takes around 40% of the gait cycle. The motion of the foot, from heel contact through midstance to toe-off (propulsive phases), is of particular interest to clinicians because it provides information on the internal loading of the foot and the physical interaction between the foot and the surface. Thus, spatiotemporal, kinematic and kinetic parameters have been generally researched as the main parts of the human gait**.**

### 2.4.2. Gait measures

To study the human gait, some major groups of gait parameters should be considered. The most common types of parameters researched in gait analysis can be subdivided into spatiotemporal, physical dimensions of humans (anthropometric), kinematic and kinetic variables. These parameters are defined below. Spatiotemporal data provide a basic description of time and distance parameters during which movement takes place, namely stride and step length, step width, cadence, velocity, and phases (stance and swing) (Miyazaki et al., 2002; Lynn et al., 2007). Kinematic parameters include the acceleration of body segments, joint angles, angular motion as well as tracking coordinates (X, Y, and Z) and orientation. Kinetic refers to the study of force (F), such as ground reaction force (GRF) that causes human movement.

There is a useful set of information regarding GRF. For instance, plantar pressure measurements are associated with GRF (Muro-de-la Herran et al., 2014). Plantar pressure provides information about the function of the ankle and foot during gait. The most important clinically relevant variables are peak pressure (PP), pressure time integral (PTI), contact area (CA), contact time (CT) and centre of pressure (COP). Moreover, PP, PTI, CA, CT are plantar pressure measures commonly assessed during gait (Putti et al., 2008; Keijsers et al., 2010). PP is the single most generally reported measure and represents the maximum load in the plantar surface of the foot or given the area of the foot during gait (Bus & Waaijman, 2013; Keijsers et al., 2010; Melai et al., 2011). This is clinically important because the magnitude (the bulk) of PP can be localised to the plantar surface when walking (Melai et al., 2011). The PTI is defined as the area under the pressure-time curve within each foot mask and is expressed in kilopascals multiplied by seconds (Rao et al., 2011; Redmond et al., 2008). The PTI describes the total effect of pressure over time in a given area of the foot, providing a value for the total load exposure of the sole of the foot area with each step (Melai et al., 2011). Those with forefoot pain have been found to have significantly higher levels of PTI compared to healthy controls (Keijsers et al., 2010). The CT is also a clinically relevant measure as it indicates the time in milliseconds. Through the stance phase, each area of the foot is in contact with the pressure pad (Putti et al., 2008). Knowing contact time can aid in understanding loading patterns can identify compensations or fear-avoidance associated with loading the painful area (Rao et al., 2012).

All gait analysis information can be achieved using several types of sensors. For example, kinetic analysis involves the study of plantar pressure with pressure mats or insoles devices and GRFs. Moments and pressures are recorded through force plates. Kinematic analysis studies motion captured with a three-dimensional (3D) system, joint angles with goniometers, evaluating acceleration with SMAs and actions of muscles with electromyography (EMG) (Burnfield, 2010; Whittle, 2007; Mathie et al., 2004). These are presented in **(Figure 2.7**).

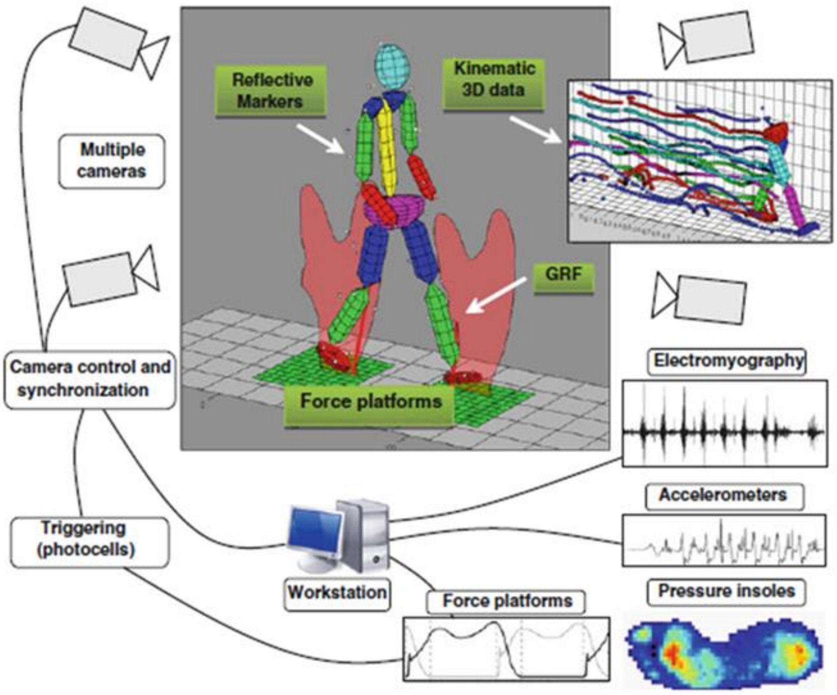



**Figure 2.7.** Systems in normal gait laboratory, utilizing photocells for synchronizing both camera system and force platforms. Further, accelerometers, electromyography, and pressure insoles can be used (Lyytinen et al., 2014)

## 2.5. Plantar pressure

All bodies load the ground due to the gravity force. Human bodies load the ground in the sitting, standing, lying and walking status. The counteracting force (F), ground reaction force (GRF), is transmitted through human bodies and is felt like pressure. Forces acting over small areas produce high pressure, however, a larger area (with equal force) reduces the pressure, as presented in the following equation for pressure:

**P=F/A …………………………………. (2.1)**

Where: P (pa) is pressure, F (N) is the force and A ($m^2$) is an area

A high PP damages skin, other soft tissues, and underlying structures. Plantar pressure is mainly measured in gait laboratories and clinical practices. The two most common techniques utilised are barefoot measurements and in-shoe pressure measurements. The design of barefoot measurement platforms varies - some are large and can register several steps (**Figure 2.8),** while others such as walkway platforms, measure single steps.

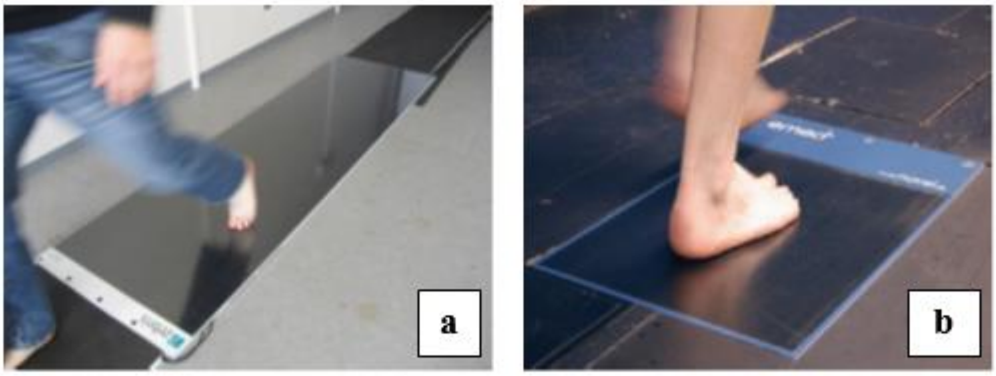



**Figure 2.8.** The plantar pressure platform registers several steps while the patient walks barefoot a- foot plantar pressure system by Zebris Medical GmbH. b- plantar pressure sensor emed® by Novel (cited by Razak et al., 2012)

Plantar foot ulcers typically develop at points of the foot where there is high pressure. Sites of increased pressure typically occurs over bony prominent areas during walking (Ledoux et al., 2013). A number of studies (e.g. Waaijman et al., 2012) have reported that the most common locations of plantar foot ulcers are in toes and metatarsal heads (Waaijman et al., 2012). It is reported the most common position of foot sores occur at the first metaphalangeal joint region (27%), followed by the hallux position (18%) (Waaijman et al., 2012). Furthermore, it is clear that there is a correlation between the site of the ulcer and the magnitude of pressure. Consequently, it is important to gain a thorough understanding of the varied factors that may influence plantar pressure during walking (Hessert et al., 2005).

Levin and O'Neal (1988) explain that the foot skin acts as a mechanical protective layer which shields the foot from external stresses. Plantar soft tissue is constructed of three layers: the epidermis (the outer layer), dermis (second layer) and subcutaneous tissues (the layer between the skin and muscle), as shown in **(Figure 2.9)**. In addition, these tissues comprise a number of layers of skin, fat, fascia and muscle, which work together to provide cushioning during walking (Chao et al., 2011). The process of increased pressure and foot ulceration originates from alterations to deeper layers of soft tissue (Chao et al., 2011). Murray et al. (1996)

point out that dry skin, in combination with high plantar pressures, and the repetitive nature of walking leads to the formation of a callus (toughened area of skin) under prominent bony areas, including the metatarsal heads. The process of keratinisation is stimulated by overactivity due to the repetitive compression applied during walking. This result in hypertrophy of the stratum corneum, is thought to increase the proliferation of epidermal cells (Murray et al., 1996). A callus increases the risk of developing an ulcer. This is due to the increased hardness and density of the skin which increases pressure during walking (Reiber et al., 1998). This research indicates that changes to tissue morphology can influence biomechanical properties, which have the potential to affect cushioning.

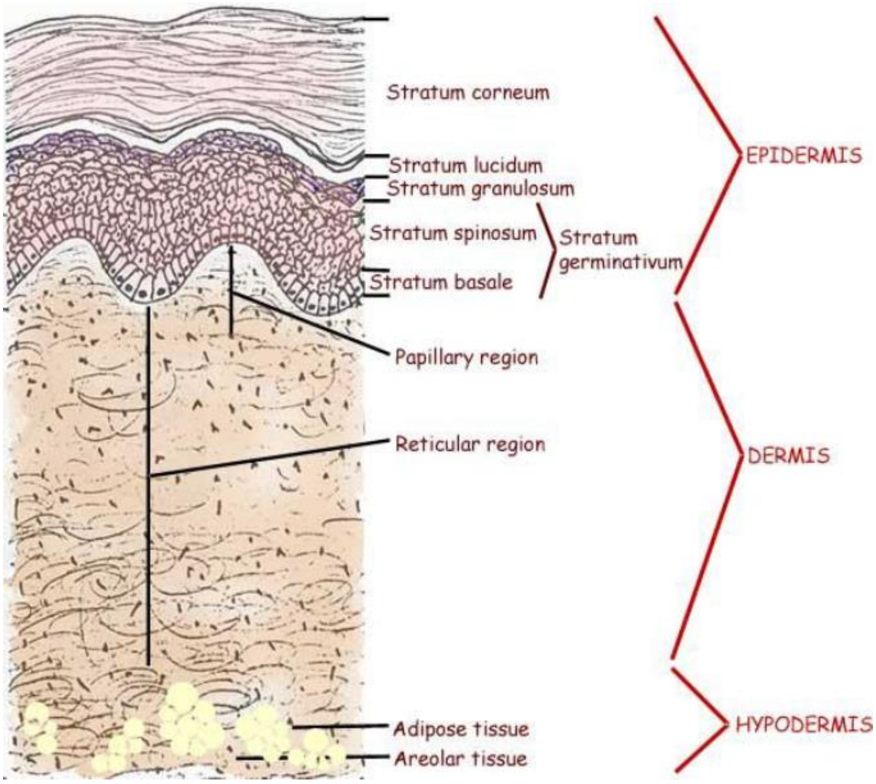



**Figure 2.9.** Layers of the plantar skin

### 2.5.1. Plantar load distribution: an overview

In both clinical practice and research studies, plantar load distribution has become a significant tool for assessing human gait (Orlin & McPoil, 2000; Monteiro et al., 2010). As mentioned in the prior section, plantar loading is a term used to refer to the vertical ground reaction forces exerted on the plantar surface of the foot. The study of plantar load distribution is important for the understanding of human foot biomechanics, foot stress, foot injury mechanisms, and foot neuropathy diseases, such as diabetes (Maetzler et al., 2010; Perttunen, 2002; Castro et al., 2013; Mohd Said et al., 2016).

In fact, plantar load distribution studies are of particular interest as they provide direct and detailed information on the ground reaction forces or pressure acting on foot regions, and the physical interactions between the foot structures and the supporting surface (ground interaction) (Alexander et al., 1990; Orlin & McPoil, 2000; Titianova et al., 2004). Normally, plantar load distribution investigations emphasise the determination and analysis of GRF or pressures acting on the foot regions during static (standing) or dynamic (walking) conditions (Vereecke et al., 2003; Giacomozzi & Martelli, 2006; Mao et al., 2006; Menz & Morris, 2006). Usually, the interaction between the sole of the foot and the supporting surface is presented either by GRF graphs or by a pressure map, which depicts the values of localised and mean pressures (Hayafune et al., 1999; Perttunen, 2002).

Several conditions influence plantar load distribution as load distribution characteristics differ from person to person due to a range of factors, like variations in body weight (Menz et al., 2006; Martínez-Nova et al., 2008; Rodrigo et al., 2013; Yümin et al., 2016), walking speed (Taylor et al., 2004; Menz et al., 2006), gender (male and female) (Bennett & Duplock, 1993), foot shape (Chuckpaiwong et al., 2008), age (Morag & Cavanagh, 1999; Scott et al., 2007; Menz et al., 2006; Martínez-Nova et al., 2008; Yümin et al., 2016), foot geometry (Hayafune et al., 1999), race differences (Putti et al.,2010) and stride length (Menz et al., 2006; Martínez-Nova et al., 2008). Conversely, it has been hypothesised that body weight, pacing velocity and the structural variations in the foot arch have significant influences in changing foot load distribution (Taylor et al., 2004; Menz et al., 2006; Chuckpaiwong et al., 2008; Chang et al., 2012). Hence, a component of the current investigation focuses on identifying the influence of body weight, age and self-selected speed foot movement (gait) on changing plantar load distribution.

Plantar loading has been extensively observed in static (Mao et al., 2006) and dynamic situations (Vereecke et al., 2003; Giacomozzi & Martelli, 2006; Mao et al., 2006; Menz & Morris, 2006; Patry et al., 2013). It has been reported that each foot carries about half (50%) the body weight during normal stance (Bennett & Duplock, 1993; Antunes et al., 2008; Cheng et al., 2008), with the highest plantar pressure distributed under the heel (H), forefoot and big toe ($1^{st}$T), and the lowest plantar load located under the midfoot (MF) (Perttunen, 2002).

However, the plantar pressure distribution map alters noticeably during foot movement (Taylor et al., 2004; Chuckpaiwong et al., 2008). Previous literature has indicated that an increase in the speed of foot movement leads to an increase in PP in the H, medial and central metatarsals and $1^{st}$T region and excludes the medial foot and lesser toes (Perttunen, 2002; Mao et al., 2006; Morag & Cavanagh, 1999; Menz & Morris, 2006). Hennig et al. (1994) indicated that PP transfers sequentially from the H region to the metatarsal heads between the early and late stance. Hayafune et al. (1999) reported that during the late stance phase, the load acting on the first metatarsal head (1MH) and second metatarsal head (2MH) and the $1^{st}$T region is about 64% of the total forefoot load. Perttunen (2002) reviewed and summarised the values and the locations of PP during walking, relying on previous research **(Figure 2.10).** This data clearly shows that during foot movement, the PP is transformed rapidly from the rearfoot to the forefoot. The regions under the H, medial and central forefoot and $1^{st}$T, exhibit the highest PP value.

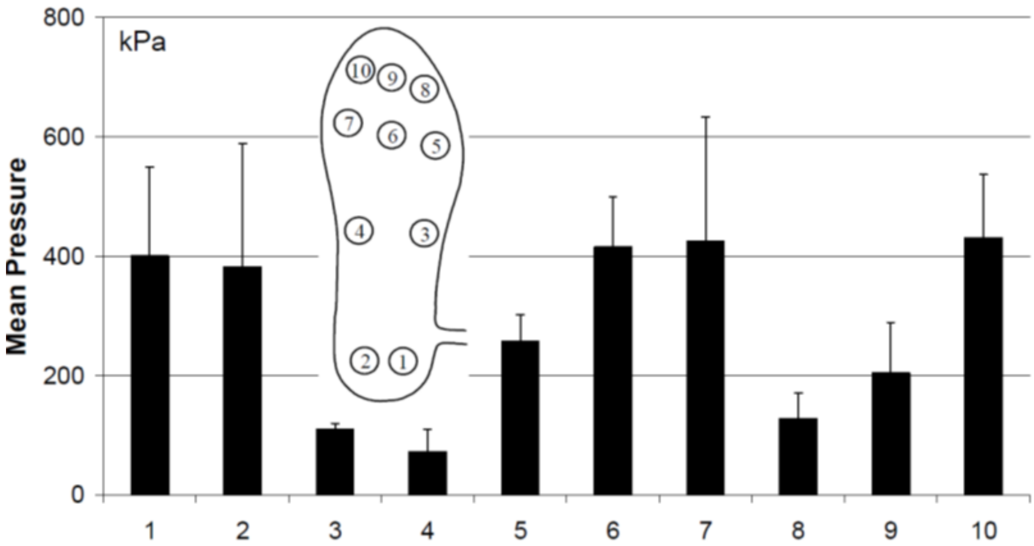



**Figure 2.10.** Mean and SD for the peak plantar pressure during walking (Perttunen, 2002)

### 2.5.2. Foot plantar pressure mask or anatomical regions

Foot plantar anatomical regions measure the foot plantar pressure, with various sub-areas of the sole (Walker & Fan, 1998; Bryant et al., 2000; MacWilliams et al., 2003). Analysing pressure data begins with the first stage, which is to divide the plantar area into different sub-areas of interest on the sole, to obtain clinically applicable data from a large number of sensors. The common, as well as a necessary method of investigating plantar pressure, is to 'mask', to define the regions of high risk (Cavanagh et al., 1992). A mask simply defines the borders of the foot into anatomical regions of interest to provide more clinically relevant information than observation of the foot as a whole (Razak et al., 2012). Specific plantar pressure variables can be computed for each person, region or mask. Such auto masks have been applied to analyse the plantar pressure or normal walking parameters (Bryant et al., 1999; Bryant et al., 2000) and various foot deformities (Bus et al., 2005, Orendurff et al., 2006). Analysis of load or pressure distribution applied to the plantar surface of the foot is undertaken by dividing the plantar surface into a number of regions. The number of regions within the foot varies among researchers from two to ten regions. The selection of the number, name and areas of foot regions may differ between researchers based on the purpose of the study. The numbers and names of the foot regions are displayed in detail below, according to the previous studies. For example,

a) Two regions: A foot is divided into two areas: the forefoot and hindfoot (Dowling et al., 2001).

b) Three regions: The foot is divided into three sections: rearfoot, midfoot, and forefoot (Oatis, 2009), otherwise known as forefoot, midfoot, and hindfoot (Bedi and Love 1998).

c) Four regions: For the purposes of analysis, there are a number of ways of categorising the foot: Vela et al. (1998) evaluated pressures located under the H, MF, 1MH, 2MH through 5MH regions. Pirozzi et al., (2014) considered areas under the H, MF, forefoot, and 1MH). Birtane and Tune (2004) included different anatomical foot locations (forefoot, rearfoot, total plantar, and forefoot plantar).

d) Five regions: The foot regions were divided into five regions, described in two different ways: H, MF, forefoot, $1^{st}$T and lesser toes (Walsh et al., 2017); or five anatomical foot areas called H, MF, MHs, $1^{st}$T and the lateral four toes (Elnaggar, 2016).

e) Six regions: Studies have divided the foot sole into six anatomical regions. Cousins et al. (2013), for example, divided the regions into six, namely lateral H, medial H, MF, 1MH, 2MH to 5MH, and $1^{st}$T. Mueller et al. (2016) considered six-foot regions: total foot, toes, forefoot, medial MF, lateral MF and hindfoot. Nyska et al. (1997) showed that the foot can be divided into six regions H, $1^{st}$T, $2^{nd}$ to $5^{th}$ toes, metatarsal region, medial MF, and lateral MF. Arnold et al. (2010) divided the foot into six regions, namely (M1 Hallux, M2 Lesser Digits, M3 First Metatarsal, M4 Second to Fifth Metatarsals, M5 MF, and M6 H). The masks mentioned above were developed to produce six anatomical regions; whole foot, H, MF, forefoot, $1^{st}$T and toes (Butterworth et al., 2015). And, described another way, six anatomical regions: H, MF, 1MH, 2-5MHs, $1^{st}$T, and lesser toes (Bus & de Lange, 2005).

f) Seven anatomical foot locations, called the posterior and anterior H, 1MH, 2MH, 4MH, 5MH, and $1^{st}$T (Zhu et al., 1991). According to Femery et al. (2003) seven areas were identified under the lateral H, medial H, the fifth (M5), the third (M3) and the first (M1) metatarsal heads and the $1^{st}$T. Speksnijder et al. (2005) called the areas H, MF, lateral forefoot, central forefoot, medial forefoot, $1^{st}$T and $2^{nd}$T to$5^{th}$T.

g) Eight regions: Hills et al. (2001) evaluated eight anatomical foot locations (H, MF, I –VMHs, $1^{st}$T).

h) Nine areas under the foot: H, medial MF and lateral MF, $1^{st}$T, and each of the five metatarsals (Phethean & Nester, 2012). Maetzler et al. (2010) also divided the foot into nine regions: H, MF, 1MH to 5MHs, $1^{st}$T and $2^{nd}$T to$5^{th}$ T.

i) Ten regions, medial and lateral heel (HM and HL), metatarsal areas (M1–M5), MF, $1^{st}$T and $2^{nd}$-$5^{th}$T were described by Monteiro et al., (2010). In addition, Mickle and Steele (2015) described ten anatomical landmarks: H, MF, 1MH, 2MH, 3MH, 4MH, 5MH,$1^{st}$T, $2^{nd}$T and $3^{rd}$-$5^{th}$T. The foot was divided into ten regions: H, MF, 1MH to 5MH, $1^{st}$T, $2^{nd}$T and $3^{rd}$–$5^{th}$T by Putti et al. (2008); Putti et al. (2010). These regions are displayed in **(Figure 2.11),** and the symbols (a, b, c, d, e, f, g, h, and i) were given to indicate the number of regions of the foot.

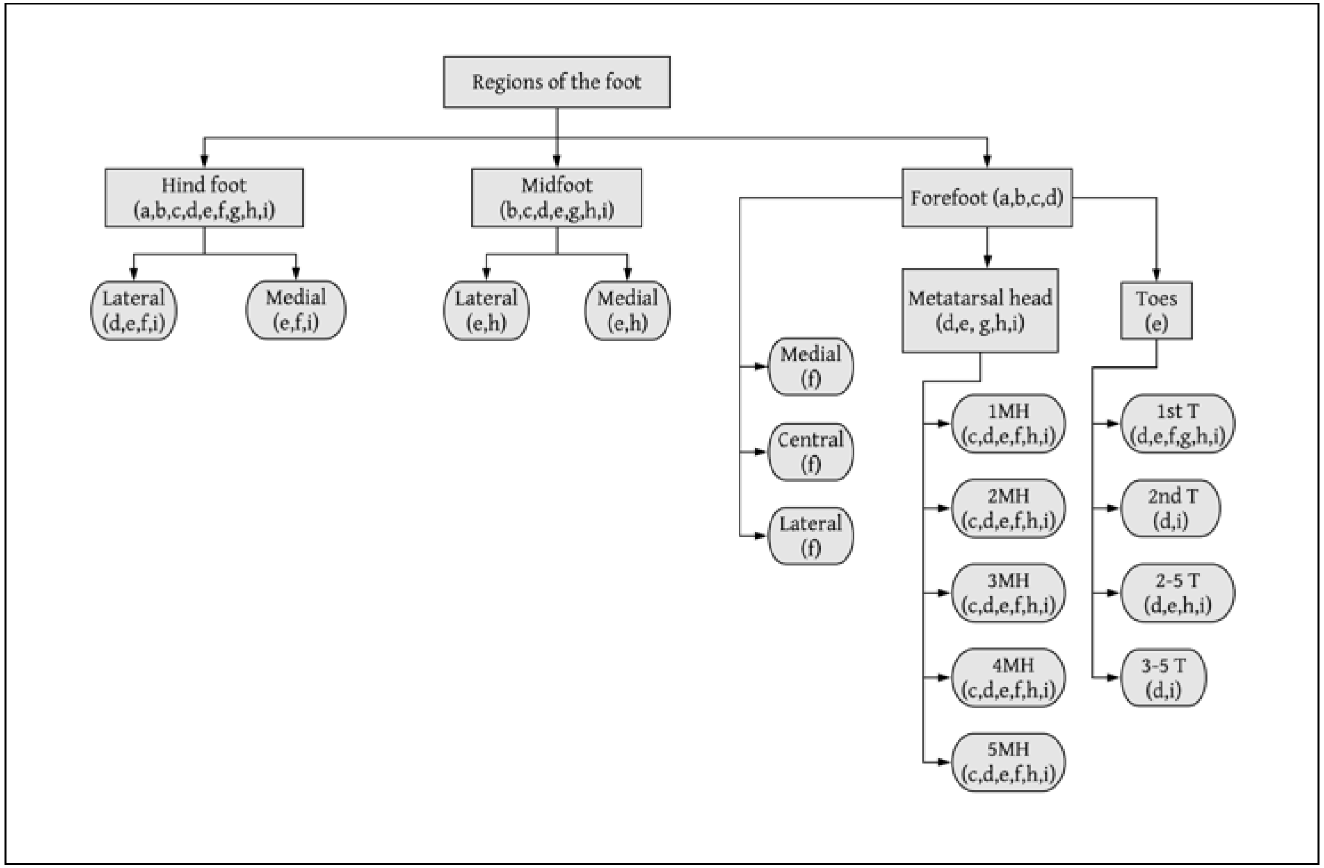



**Figure 2.11.** Illustration of the variety of foot regions

This figure shows the foot divided into three regions, namely the forefoot, midfoot and hind foot. These zones can be reproduced by software provided by the various in-shoe or pressure platform systems. The number of regions varies among researchers from two to ten, foot regions (Putti et al., 2008; Putti et al., 2010; Birtane & Tuna, 2004; Chevalier et al., 2010; Bennett & Duplock, 1993; Hills et al., 2001; Ho et al., 2010; Aydos et al., 2012). However, most researchers who have investigated the plantar loading of children and adults agree that the plantar is divided into ten anatomical regions **(Figure 2.12).**

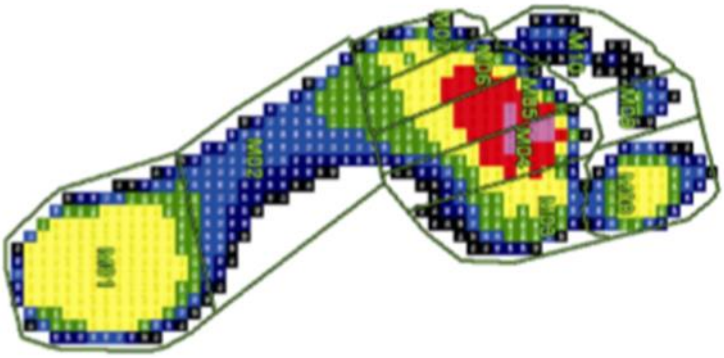


**Figure 2.12.** Ten anatomical regions of the foot defined for plantar pressure distribution analysis. M01: Heel, M02: Medial midfoot, M03: 1 MT Head, M04: 2 MT Head, M05: 3 MT Head, M06: 4 MT Head, M07: 5 MT Head, M08: Hallux, M09: M10: Toes (Putti et al., 2008)

### 2.5.3. Plantar pressure distribution

Plantar pressure assessment is commonly used in the clinical evaluation of the foot and provides insight into plantar loading characteristics during functional activities, such as walking and running. Currently, in-shoe pressure systems provide two techniques for presenting either through means of pressure or forces measured reaction of the sole to the ground. Many researchers have analysed plantar pressure for healthy participants (Bryant et al., 2000; Putti et al., 2008; Putti et al., 2010; Putti et al., 2010; Maetzler et al., 2010) and others have analysed overweight and obese populations (Vela et al., 1998; Putti et al., 2008; Hills et al., 2001; Dowling et al., 2001; Birtane & Tune, 2004; Fabris et al., 2006). These have been used in various studies to detect foot pathologies in different age groups (adults and children), whether healthy or overweight or obese. These studies have identified pressure characteristics during gait, the contact area of the plantar aspect of the foot and the forces produced. There are a range of devices available to measure these characteristics during barefoot and in-shoe pressure measurements.

#### 2.5.3.1. Normal plantar pressure measurements

In a previous study by Bryant et al. (2000) with respect to PP distribution on ten masked areas, the maximum mean values were found under the H, 2MH and 3MH, and $1^{st}$T regions. The least variation of plantar pressure (mean and peak pressures) was found under the H and the 2MH and 3MH regions. The greatest variations were found under the toes and MF. This may be due to variability in arch heights, as other studies have confirmed this variation (Goffar et al., 2013). Kanatli et al. (2008) studied plantar pressure distribution under the forefoot of 106 normal participants via an Emed-SF® method.

They divided the foot into the medial column (1MH), middle column (2MH and 3MH) and lateral column (4MH and 5MH). They found that during the midstance and the push-off phase of gait, the mean and PPs were the highest under the 2MH and 3MH regions. Their study questioned the existence of the transverse metatarsal arch during gait. The absence of the transverse metatarsal arch was supported in the previous study where they showed that the transverse arch collapses during the push-off phase (Kanatli et al., 2003). This questions the tripod theory proposed by Kapandji (1970) which states that the longitudinal and transverse arches of the foot result in weight-bearing like a tripod between H, 1MH to 5MHs. Other investigators have questioned the presence of the transverse arch using ultrasonography on hundred healthy subjects and measured plantar pressures of the forefoot using an Emed-SF® system (Daentzer et al., 1997). Using ultrasound measurements in the weight bearing position, they found 2MH to 4MHs to be in a more plantar position and the maximum plantar pressure measured by an Emed-SF® system to be present in the 3MH region. With respect to PTIs, Bryant et al. (2000) reported that the highest measurements were under the 2MH and 3MH and the $1^{st}$T, and the greatest variation was noted beneath the 5MH and toe.

Putti et al. (2008) completed an evaluation of foot pressure values in the healthy individual. The authors recruited 53 normal weight individuals (17 women and 36 men) aged between 19 and 52 years. An Emed ST4 system was utilised to gather the foot pressure data. The authors divided the foot plantar into ten regions. They selected six of the most clinically relevant parameters which were PP, CA, CT, PTI, FTI and IPP. They established that the highest areas of PP were found under the 2MH and 3MHs, with the mean equal to 361 kPa and 330 kPa, respectively, followed by the 1$^{st}$T with 321 kPa and H with 313 kPa. CA was the highest under the H strike at 35 cm$^2$. The percentage of CT was in the range of 75-85% under the MHs, and 70% under the 1$^{st}$T. Additionally, PTI was the highest under the 1MH to 3MH and 1$^{st}$T at 87 kPa/s, 107 kPa/s, 104 kPa/s, and 87 kPa/s, respectively. FTI value was the greatest beneath the H region at 105 N/s. The ranges of parameters can be applied in orthopedic clinics as part of the assessment of pathological conditions.

Putti et al. (2010) investigated in-shoe pressure differences between two different racial groups of 33 participants comprised of 12 Caucasians aged between 19–52 years and 21 persons from India age between 21-46 years. The authors divided the foot into 10 regions. They were selective in their investigation and recorded eight of the most clinically significant parameters, which were IPP, maximum F (max F), PP, CA, CT, PTI, FTI, and mean F. They concluded that the Caucasian group was higher than the Indian group within two pattern parameters, those being PP and PTI in particular, the PP under the H was 293 kPa versus 251 kPa; ($P < 0.001$), under 1MH was 294 kPa versus 233 kPa; ($P = 0.01$), under 2MH was 266 kPa vs. 236 kPa; ($P = 0.03$), under 3MH was 254 kPa vs. 223 kPa; ($P = 0.04$), and 5MH was 168 kPa versus 133 kPa; ($P = 0.04$) and the PTI under 1MH was 79 kPa/s versus 62 kPa/s; ($P = 0.03$) and under 5MH was 58 kPa/s versus 44 kPa/s; ($P = 0.03$). There were no significant differences in the CA, CT, FTI, IPP, max F and mean F variables between the two groups.

Putti et al. (2010) investigated any potential foot pressure differences between males and females using an in-shoe measurement for ten different regions of the foot for all the important pressure measurement characteristics. Twenty-eight subjects (16 females aged between 19-52 years and 12 males aged between 21-52 years) were recruited. In their examination, the researchers selected eight of the clinical parameters, (CA, CT, PP, PTI, FTI, IPP, mean F and max F) which were recorded and analysed. The authors observed that the contact area in males was significantly larger in all regions of the foot compared with females ($P < 0.001$). They found a higher value within the H region (44.1 $cm^2$ for male and 34.1 $cm^2$ for females). Furthermore, FTI was also significantly higher in males under the 1MH, 3MH, and 4 MH (58, 35, 26 N/s), while in females these were 41, 21, 13 N/s respectively. Also, the max F was also significantly higher in males under the H area compared to females (701 N and 525 N), 1MH (216 N and 168 N) and 3MH (115 N and 77 N). The mean F was greater in males under the 1MH, 3MH, and 4MH. The authors found that there were no significant differences between genders in CT, PP, PTI and IPP in the foot.

Maetzler et al. (2010) measured pressure value in the normal foot with the Emed1 ST2 system (barefoot). Twenty-three subjects (fourteen females and nine males) with mean age of 36.0 ±11.6 years participated. The authors divided the foot into 10 regions to record seven-foot pressure variables: beginning of contact, end of contact, CT, PP, IPP, CA and PTI. The highest areas of PP were found under the $1^{st}$T and 2MH, with mean equal to 435 kPa and 407 kPa, respectively, followed by the 3MH of 345 kPa and the hindfoot of 332 kPa. The CT (range of pressure, %) was 74–85% under the MHs, and 71% under the $1^{st}$T. CA was the highest beneath the H region at 33.8 $cm^2$.

#### 2.5.3.2. Overweight and obese plantar pressure

One of the first examples of investigating plantar foot pressure is presented in Vela et al. (1998), who used an in-shoe pressure measurement system to compare the effect of increased body mass on peak plantar foot pressure. In this test, the authors employed 19 adult participants (10 male and 9 female) under modified body weight. The authors used three weights to simulated body weight (0, 9.1 and 18.2 kg). They divided the foot sole into four regions: H, MF, 1MH, and two to five MHs. The authors found a significant increase in mean PP under the MHs, H, and MF for each incremental increase in weight (baseline vs.9.1 vs.18.2 kg, $p < 0.05$). The authors deduced that increases in body weight increased plantar foot pressure for the H, MF, 1MH and lesser metatarsal zones in both genders. The most common change in the plantar pressure came as a result of the change in body weight (mass). It was demonstrated that there was increasing plantar foot pressure in the H, MF, and forefoot with increasing weight, and they concluded that increased weight could increase the risk of lower extremity ulceration in the setting of other pathophysiologic features (Vela et al.,1998).

Dowling et al. (2001) examined foot plantar pressures during static and dynamic conditions in 13 obese and 13 non-obese children (mean age 8.1 ± 1.2 years). Each dynamic pressure footprint was divided into two areas, the forefoot and hindfoot. The obese group demonstrated greater PF under both forefoot (341.0±93.6 and 227.5±33.9 N for obese and non-obese subjects respectively) and hindfoot (446.6±83.9 and 311.0±55.0 N for obese and non-obese subjects respectively) areas but this was distributed over a larger surface area (total foot area 97.1±11.9 versus 74.3±9.2 $cm^2$). Therefore, hindfoot PP (force/area) was not significantly different between the obese and non-obese groups but forefoot PP was (39.3±15.7 $N/cm^2$ versus 32.3±9.2 $N/cm^2$). The authors reported that increased forefoot plantar pressures in obese children might lead to discomfort and hinder participation in physical activity. A limitation of this study was the division of the foot in half to describe the forefoot and hindfoot eliminating important findings that may have been found under the MF region.

More than a decade ago, Hills et al. (2001) used a pressure platform device to collect the plantar pressure data to investigate plantar pressure differences between obese and non-obese adults during standing and walking. In the test obesity was defined as a BMI greater than 30 $kg/m^2$. The study was conducted on 35 males (age 42.4±10.8 years; 67-179 kg) and 35 females (age 40.0±12.6 years; 46-150 kg). The authors evaluated the pressure from eight anatomical foot locations: H, MF, first to fifth MHs and $1^{st}$T regions. They observed that obese subjects, both female and male showed an increased H, MF and two to four MHs plantar pressures. Also, foot width showed an increase at the forefoot during standing and walking, and higher plantar pressures of the MHs and longitudinal arch areas (Hills et al., 2001). They concluded that comparing the healthy group to the obese group showed increased forefoot width and higher plantar pressures during standing and walking. The greatest effect of body weight on higher PP in the obese was found under the longitudinal arch of the foot and under the metatarsal heads. The higher pressures for obese women compared to obese men during static weight bearing (standing), may be the result of reduced strength of the ligaments of the foot. It was estimated that the ground reaction forces experienced by the lower limbs of a healthy weight individual could be as large as three to six times their own body weight. They discovered that obese adults produce greater plantar loading than non-obese adults, particularly in the H, MF and forefoot regions. In addition, obese adults had greater CA of the MF region compared to non-obese adults.

Birtane and Tune (2004) aimed to compare the plantar pressure distribution in obese and healthy adults during standing and walking using a mini-Emad pedobarograph device. Fifty participants; twenty twenty-five healthy aged mean ± SD (48.0 ±12.2) years and twenty- five persons obese Class 1 aged mean ± SD (53.0 ±9.5) years. The authors evaluated both the static and dynamic states. They assessed eight parameters during static measurement, which were forefoot PP value ($N/cm^2$), rearfoot PP value ($N/cm^2$), total plantar F (N), forefoot plantar F percentage, rearfoot plantar F percentage, total CA ($cm^2$), forefoot plantar CA percentage, and rearfoot plantar CA percentage. In addition, seven parameters were measured during the dynamic measurement. These were peak phalanx pressure ($N/cm^2$), medial forefoot peak pressure ($N/cm^2$), middle forefoot PP ($N/cm^2$), lateral forefoot PP ($N/cm^2$), middle foot PP ($N/cm^2$), rearfoot PP ($N/cm^2$), and plantar CA. Birtane and Tuna (2004) reported that, out of six plantar regions, only the MF area recorded a statistically significant increase in peak plantar pressure when obese subjects (BMI between 30.0 - 34.99 $kg/m^2$) were compared to non-obese controls. For the feet of Class 1 obese subjects in the static condition, they found that there were significantly higher values in terms of forefoot PP, total plantar force and total contact area, while only middle foot PP was found to be higher in Class 1 obese subjects than controls, as a dynamic pedobarographic parameter. Moreover, Birtane and Tune (2004) compared the plantar pressure distribution variables that measured obese and control adults during standing and walking, based on the body mass index. They found the r-value of the variables that were measured were between weak to moderate, which may be required consideration. They emphasised that the facts might be the result of mechanisms of adaptation to weight bearing vertical force acting in the plantar arch due to obesity (Birtane & Tuna, 2004).

## 2.6. Pressure measurement techniques

In research or clinical work, there is a diversity in approaches utilised to measure vertical components of the GRFs or pressure that is applied to the human foot plantar surface during static or dynamic situations (Abdul-Razak et al., 2012; Symiya et al., 1998; Perttunen, 2002; Vereecke et al., 2003; Bryant et al., 2005; Noce, 2005; Giacomozzi & Martelli, 2006; Kalamdani, 2006; de Souza, 2007; Rana, 2009; Abdul-Razak et al., 2012; Rodrigo et al., 2013; Muro-de-la-Herran et al., 2014). Researchers have described three approaches for measuring plantar pressure (Perttunen, 2002; Orlin & McPoil, 2000). Firstly, the assessment of plantar pressure or GRF between the plantar surface of the bare foot and ground support. Secondly, determining pressure or GRF interaction between the sole of the shoe and the ground support and thirdly, measuring pressure between the plantar surface of the foot and the insole of the shoe. The current investigation emphasises the third assessment approach because it can be adopted to study a cargo distribution on the foot plantar zones of the in-shoe, which is the central and major clinical purposes of this study.

### 2.6.1. Pressure and ground reaction forces measuring systems

Throughout the development of pressure and GRF measuring systems, valuable and specific information has been obtained about the ground reaction forces and the pressure load distribution, which results from the interaction between the static or moving foot and the supporting surface (Perttunen, 2002; Vereecke et al., 2003; Noce, 2005; Giacomozzi & Martelli, 2006; Kalamdani, 2006; de Souza, 2007; Rana, 2009; Abdul-Razak et al., 2012; Muro-de-la-Herran et al., 2014). **Figure 2.13 (a, b)** shows that the main difference between these techniques is the variety of devices or systems employed to record and capture the human foot load (pressure) during standing or moving conditions. Generally, the plantar load measuring systems have been classified into two main classes, a pressure measuring systems and a GRF measuring system (Shi, 2001; Perttunen, 2002; Bryant et al., 2005; Noce, 2005; Abdul-Razak et al., 2012). Currently, a number of measuring system products are commercially available, **(Figure 2.13 (b))** such as a foot insoles, pressure pads, (Vereecke et al., 2003; Kalamdani, 2006; de Souza, 2007); Pedar (Abdul- Razak et al., 2012; Muro-de-la-Herran et al., 2014; Noce, 2005); F-Scan (Tekscan), and pressure platform systems (Noce, 2005; Rana, 2009). In addition, a force plate (e.g., AMTI) and wearable force sensors are commonly utilised to measure a GRF of the moving foot (Perttunen, 2002; Giacomozzi & Martelli, 2006; Liu et.al., 2009; 2010; Rupérez et al., 2009; 2011) for instance, the flexi-tactile sensor system Nitta Corporation, (**Figure 2.13 (a)).** Technically, in this study each foot load measuring system used to measure plantar load or plantar pressure has several advantages and a number of limitations (Noce, 2005; Abdul-Razak et al., 2012).

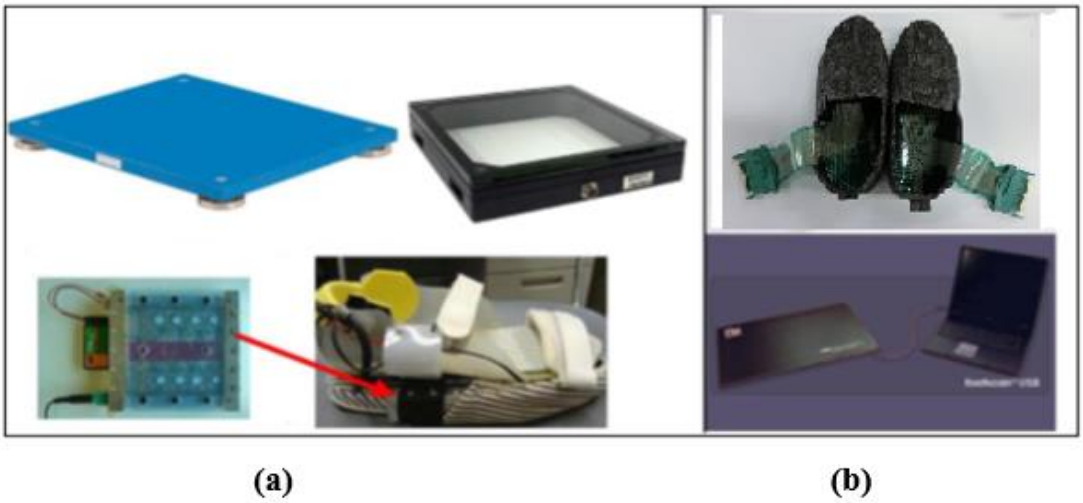


**Figure 2.13.** (a) Ground reaction forces measuring system; (b) Pressure measuring systems (Chong et al., 2015; Al-Magsoosi & Chong, 2019)

### 2.6.2. Foot pressure measurement systems

Foot pressure measurement methods include electronic systems intended to assess the foot pressure that measures the consequence from the interaction within the foot and the support surface (Shi, 2001; Perttunen, 2002; Noce, 2005; Bryant et al., 2005; Martínez-Nova et al., 2008; Flórez & Velásquez, 2010). These systems can be utilised to determine the vertical forces (FZ) applied by the human foot by integrating individual pressure distributions (Shi, 2001). Generally, foot pressure measurement systems consist of several tiny pressure sensors, thus, these systems are perfect for assessing plantar pressure without disturbing the subject or patient’s movement during testing because they are thin enough, which allows non-intrusive assessment, as seen in (**Figure 2.14)** (Noce, 2005; Bryant et al., 2005; Abdul-Razak et al., 2012; Rodrigo et al., 2013). Moreover, pressure systems are useful devices in clinical walk test studies for (Abdul-Razak et al., 2012; Bryant et al., 2005; Rana, 2009) foot detection and rehabilitation (Abdul-Razak et al., 2012), footwear design, biomechanics (Rana, 2009) and sport enforcement (Orlin & McPoil, 2000). A number of scientific researchers have noticed that pressure systems can provide sufficient outcomes on testing human gait compared to the more precise information of the force plate (Symiya et al., 1998; Shi, 2001; Noce, 2005). Thus, they have become an indispensable tool for gait analysis in both clinical and research settings. The sensing technology is capable of measuring static and dynamic pressure, which has played a crucial role in understanding the effects of pressure on the foot (Wafai et al., 2015).

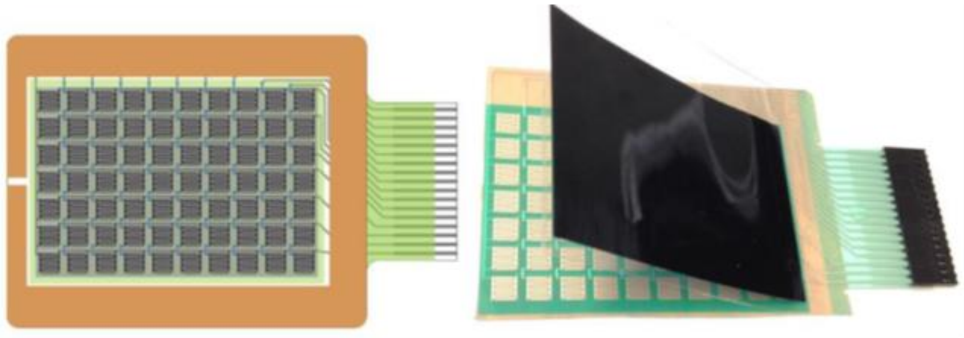


**Figure 2.14.** The matrix of force resistance sensors (Chong et al., 2015)

The lack of precision (ranging between ± 5% to ± 25%), uncertainty and differences in sensors readings, partially through the dynamic assessments, are the main limitations in methods that determine pressure (Symiya et al., 1998; Orlin & McPoil, 2000; Shi, 2001; Abdul-Razak et al., 2012). Moreover, one of the most important limitations associated with these systems is the reliance on force profile and that they do not relate to the force distribution with the movement of the foot (Orlin & McPoil, 2000). Finally, pressure measuring systems cannot determine the fore-aft or medial-lateral shear forces, considered necessary for studying the development of plantar ulcers in a diabetic’s feet (Orlin & McPoil, 2000).

Numerous technologies are employed to manufacture pressure measurement systems and they can be grouped into two kinds, in-shoe and platform (Abdul-Razak et al., 2012). The F-Scan - Tekscan® (Boston, US) insole plantar sensor pad system, also referred to as the in-shoe plantar pressure assessment, is becoming increasingly used, and is popular worldwide as both a research and clinical tool for pressure measurement and force data collection during dynamic movements. For instance, evaluating foot pressure in humans (Waaijman & Bus, 2012; Chong et al., 2017). It allows the collection of objectives, and quantifiable measures to study different types of human lower limb pathologies, and it ensures a high degree of portability in different clinical settings. It has been used for many applications, including the clinical walk test (Baan et al., 2012) and diagnosis of foot-related diseases, such as diabetic ulceration, plantar fasciitis, and arthritis (Badlissi et al., 2005). It is also a unique candidate as a pressure sensor due to its miniature size, light weight, and very good sensitivity (Baan et al., 2012). The advantages and drawbacks of these two system types are addressed in the following sections.

### 2.6.3. In-shoe pressure measurements

Recording and monitoring the local pressure values between the human plantar surface and footwear are explored by in-shoe pressure systems. This is becoming a standard in today's health assessment because of its ability to objectively characterise behaviour inside as well as outside the laboratory environment (Orlin & McPoil, 2000; Abdul-Razak et al., 2012; Muro-de-la-Herran et al., 2014). It has been well documented that plantar pressure is strongly associated with ulceration (Boulton, 2014). Therefore, in-shoe measurement is a valuable tool that can be used to provide evidence which may ultimately impact both shoe design and clinical practice (Abdul-Razak et al., 2012; Orlin & McPoil, 2000). The systems are fundamental in many aspects like medical and sports applications including human gait analysis (Abdul-Razak et al., 2012; Muro-de-la-Herran et al., 2014), orthotic design (Abdul-Razak et al., 2012; Muro-de-la-Herran et al., 2014), shoe research, and sports biomechanics (Orlin & McPoil, 2000). The in-shoe system consists of a pressure film put into the shoe, which is linked to a storage system by USB cable. Generally, a pressure film is a tiny sheet that gathers a large amount of data from such as a small pressure sensor **(Figure 2.15)**. Sensor distribution in the pressure film is high resolution in the zones of the H area and forefoot area and tends to have a low resolution in the MF area. An in-shoe pressure system can be manufactured simply, while some studies have inserted various prototype models of in-shoe methods (Noce, 2005; Bamberg et al., 2008; Rana, 2009). These are shown in (**Figure 2.15)**. Applying in-shoe pressure methods for assessing the plantar pressure of the foot comprises several of advantages and some constraints. One of the most important features of the in-shoe system is the ability to measure and analyse sequential steps, as the foot typically remains aligned with the same sensors. In addition, in-shoe systems are appropriate for enrolment pressure and interaction amidst foot and shoe. Also, these techniques are movable and flexible and can be utilised to collect pressure data without any location restrictions (in-door or outdoor). Furthermore, in-shoe pressure devices are typically less expensive than pressure platform systems (Urry, 1999; Orlin & McPoil, 2000; Abdul-Razak et al., 2012). However, in-shoe systems encompass a limited number of pressure sensors with low resolution. In-shoe systems tend to provide low precision product compared to mat methods for the sensor in the in-shoe film in line up with a non-flat surface inner footwear (Orlin & McPoil, 2000).

Caution should be taken when interpreting the results of pressure measurements because these results are dependent on the systems and techniques that have been utilised (Giacomozzi et al., 2000). Moreover, accurate calibration and equilibration of the sensors and appropriate handling of the equipment are all required to obtain valid, reliable measurements (Luo et al., 1998). In-shoe pressure measurement determines the pressure acting on the sole of the foot while the patient uses his/her shoes. A thin sensor is adjusted to fit into the shoe. In-shoe measurements allow the patient to move over a larger area. If a wireless system is used, the patient can move outdoors while the pressure is registered. However, the sensors in the in-shoe system are prone to mechanical failure as the connecting cables connecting the sensors to each other can be bent or stretched through foot locomotion (Orlin & McPoil, 2000; Muro-de-la-Herran et al., 2014). Likewise, sensor attributes and behaviour can be impacted and spoiled due to humidity and hot environment within the footwear (Abdul-Razak et al., 2012; Muro-de-la-Herran et al., 2014).

Pressure insoles seem to provide the better trade-off for gait analysis. The in-shoe measurement system is also capable of capturing multiple footsteps' data from both feet at the same time and of recording foot function patterns directly inside the shoe. During in-shoe recording, the participant is able to exhibit a natural walking pattern without the influence of targeting a force plate positioned on the floor (Tekscan, 2010). The features of the F-Scan system are similar to wireless capabilities and low-profile sensors (0.15 mm thick, pressure ranges from 345 to 862 kPa, and each F-Scan insole comprises approximately 960 sensing elements (3.9

sensels per $cm^2$) (Coda & Santos, 2015). The F-Scan system has been used for adult podiatric management. It can collect accurate, repeatable gait recordings utilising very high spatial decisions that can reach one millimetre as well as automatically averaging data points across multiple steps within one trial (Lord, 1997 cited by Pataky 2012; Randolph et al., 2000; Coda & Derek, 2015). At present, no evidence is available with regards to the repeatability and reproducibility of the F-Scan system in weight-bearing or obese adults. The findings of this research may support the application of modern in-shoe technology for future gait analysis clinical trials to clearly identify preventable biomechanical issues related to the obese adult, who is at risk of ulceration due to an imbalance in pressure distribution between the forefoot and the rear foot during walking (Ko et al., 2012).

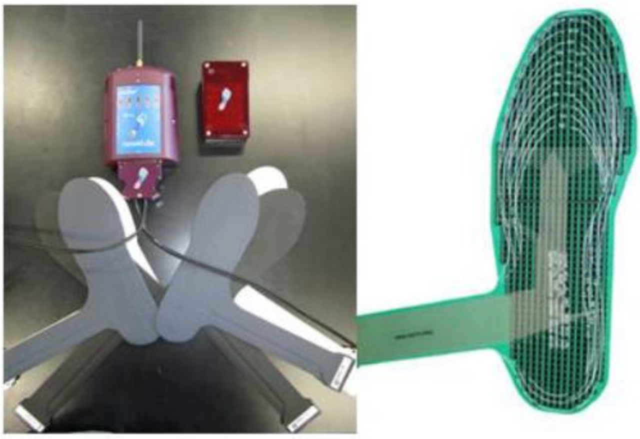


**Figure 2.15**. In-shoe pressure systems (Chong et al., 2015)

#### 2.6.3.1. Barefoot plantar pressure measurement

Platforms or mat systems have been constructed for measuring dynamic or static pressure and vertical F used for the plantar of the foot (Orlin & McPoil, 2000; Abdul-Razak et al., 2012). There are various dimensions, shapes, and resolutions of pressure mats available to accommodate a vast range of uses (Orlin & McPoil, 2000; Abdul-Razak et al., 2012). Naturally, a platform tool made up of various small electronic pressure sensors arranged in a matrix form on a circuit layer, is put among the two heat stable polyester layers (Castano & Flatau, 2014; Chong et al., 2015), as shown in **(Figure 2.16)**. Mat resolution depends on the density of sensors in the pressure sensing mat (i.e. the resolution increases with an increase in the number of sensors).

Using platform devices for gait investigations have several notable benefits. As the pressure mat is thin, it is sufficient enough to allow a non-intrusive assessment and is ideal for assessment of force without disturbing the dynamics of a trial participant, thus the system is suitable for capturing barefoot movement (Orlin & McPoil, 2000; Abdul-Razak et al., 2012). Likewise, the high density of pressure sensors within a mat system leads to the precise capturing and transmitting pressure data (Orlin & McPoil, 2000).

The pressure mat device can report the vertical force as precisely as the force plate. The mat method is generally put on a flat surface parallel to the supporting ground like the force platform system (Orlin & McPoil, 2000), presented in (**Figure 2.16)**. In addition, the sensor mat can be constructed in various resolutions and sizes with a variety of shapes that fit with specific clinical applications, such as assessing the pressure distribution between a patient's body and various supporting surfaces like seats, backrests mattresses, and cushions. These systems are often embedded into the floor or walkway and are commonly used in the analysis of barefoot pressure (Harada et al., 1999). However, there are a number of drawbacks that have been identified by previous studies regarding the employment of the platform system to capture foot pressure (Orlin & McPoil, 2000; Shi, 2001). The walkway pressure systems are better suited to reporting the pressure of bare feet in indoor environments, but they have limitations in the analysis of physical activity (Orlin & McPoil, 2000). In addition, to enhance the accuracy of collected pressure data, the subject is required to repeat each trial (crossing the walkway) between three and five times, which may be considered inappropriate and uncomfortable for patients who suffer from excessive ulcerations in their feet (Orlin & McPoil, 2000). Generally, a platform or mat system need a large environment with an appropriate setup, as a pressure mat is required to be put on a walkway to include that the trailed participant attains a steady-state walk (least three steps are gathering) prior to arrival at the mat (Shi, 2001).

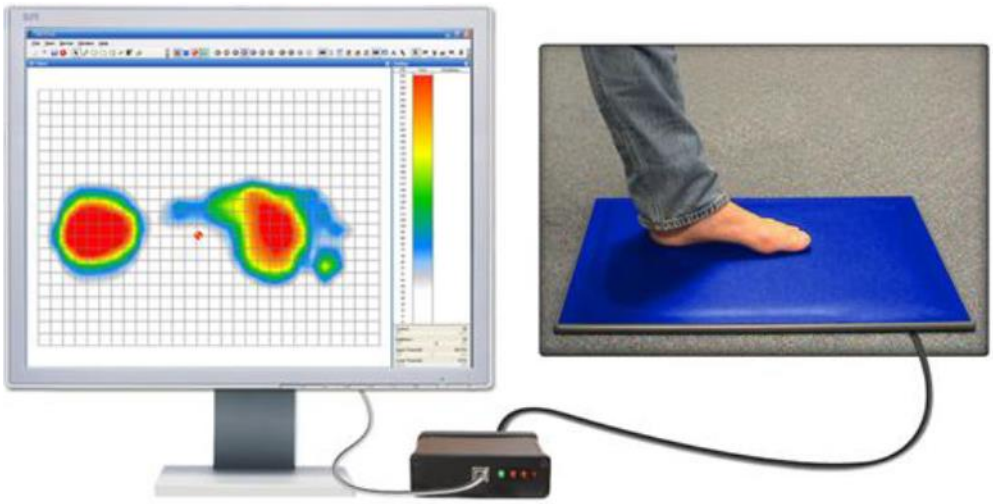


**Figure 2.16.** Platform, walkway or mat systems (Orlin & McPoil, 2000; AL-Baghdadia et al., 2015)

### 2.6.4. Sensor calibration

The electric resistance of a sensor is technically changed when a force is applied to it (Noce, 2005; Rana, 2009; Flórez & Velásquez, 2010). The loaded sensor can give readings in (either ohms or volt) units (Noce, 2005; Rana, 2009). Thus, sensor calibration has the fundamental procedure of converting the sensor output data into pressure units (Noce, 2005; Rana, 2009). Calibration is important for determining the static and dynamic characteristics of the sensor, (such as, time drift, hysteresis, and repeatability) which are necessary for applications that require force measurement accuracy. The manual sensor calibration consists of two methods. In a number of commercial foot pressure measuring systems (for example, Tekscan system), these methods are sensor equilibration and sensor calibration. The sensor equilibration process is required to minimise or compensate for small variations (i.e., hysteresis, time drift, non-linearity, creep, and repeatability) between the sensing elements on any sensor. Technically, variations result from the unique characteristics of each sensor. Moreover, the sensor calibration process converts the raw digital output data of the pressure sensor to actual pressure units, such as KPa. Based on published literature (Symiya et al., 1998; Noce, 2005; Rana, 2009), the current inquiry considers both sensor calibration procedures (sensor equilibration and sensor calibration) as a single process which is referred to as a sensor calibration process. Selecting appropriate calibration procedures can reduce the mean error in the reading of loaded sensors from 31 to 11% (Symiya et al., 1998; Shi, 2001). Sensor calibration can be achieved by using dynamic and static calibration methods. Applying both methods is considered necessary for improving sensor performance over time and the accuracy of the sensor outputs (Noce, 2005; Rana, 2009). Therefore, these calibration procedures are recommended for calibrating all foot pressure measurement systems (Noce, 2005).

## 2.7. Discussion

This review has provided a detailed discussion of some of the main causes and impacts of weight gain in humans. Furthermore, the major factors influencing the distribution of plantar loads are considered in the development of the research methodology and the selection of participants in the investigation. A review of works that have been done used normal, obese and simulated participants. It also identified a number of scientific arguments with respect to the selection of an appropriate type of loading measurement system. Therefore, the significant key points of this chapter can be summarised as follows:

1. The distribution of load on the shoe varies between individuals due to a wide range of factors such as variations in walking speed, foot shape, body weight, human age, and foot abnormality. However, it has been decided that the variation in weight has the greatest influence on changing foot load distribution;
2. In measuring plantar loading during gait, it is necessary to apply both static and dynamic calibration procedures for calibrating pressure measuring systems before using them;
3. In-shoe and mat pressure systems have suitable measuring systems and they are commercially available for recording the load acting between the plantar surface and a support surface. However, while each system has many advantages and limitations, the in-shoe is considered ideal for this research study.

## 2.8. Chapter summary

This chapter presented a literature review of 1) the effects of weight on plantar load distribution, 2) techniques recently utilised to record the loading data applied to both barefoot and in-shoe systems; and 3) the merits and drawbacks of each technique. Various theories associated with foot load distribution were reported. Body weight seems to have major influences on the distribution of the plantar load. However, the impact of these factors on gait have not been clarified in the literature. An intensive investigation of the previous literature was done in this study to find the research gap. The author found that there are limited studies that have investigated the plantar loading differences for the same weight category during gait. In addition, the review examined plantar loading measuring systems. The main emphasis focused on pressure insole methods used for measuring plantar load. A comparison between these measurement practices was performed to illustrate the feasibility of each for gait studies. The comparison found that the pressure insole is recommended for indoor as well as outdoor gait research.

The next chapter addresses the methodology that has been chosen during this research, including the instrumentation, software and participants.

# 3. METHODOLOGY

## 3.1 Introduction

This chapter focuses on describing the methodology chosen for this work and outlines the protocol used in subsequent experimental work in terms of foot plantar pressure patterns. As has become evident from the preceding chapters, foot loading has been extensively studied, especially in normal gait. In order to understand the true meaning of foot loading its measurement needs to be integrated with other measures of increased body weight. Additionally, general information on the participant’s recruitment is included. Lastly, data analysis is described on which the experiments are based.

## 3.2 Instrumentation and software

The detailed instrumentation and software of the present study can be categorised as follows:

### 3.2.1. In-shoe sensor

The in-shoe pressure assessment device (Tekscan, Boston, MA, with overall mass of 1.3 kg) was utilised to collect and evaluate the dynamic distribution of plantar foot pressure data (pressures on the sole of the foot). Recently, they have been used in a variety of studies measuring plantar pressure (e.g., Armstrong et al., 1998; Chesnin et al. 2000; Chong et al., 2017; Pirozzi et al., 2014; Waaijman & Bus, 2012). It is a system of sensors, cuffs, ankle bands, cuff cables, waist belt, USB hub, power supply and a USB cable.

Participant setup with the F-Scan® is required and undertaken by:

1. Managing the cables which are five metres in length and linked to the subject’s waist.
2. Trimming the sensors to fit any shoe presented.
3. Preparing the shoes by attaching (pasting the sensors into the shoes by medical adhesive) an insole system to the original insole of the shoe, as presented in **(Figure 3.1 A and B)**.

This system comprises a wireless transmitter and two sensor cuffs. The in-shoe sensor, F-ScanR 3000E standard was utilised. The sensors are approximately (2 mm) thick and comprised of 960 sensing elements. Plantar pressure data was recorded in kilopascals (kPa) at a frequency of 100 Hz. The frequency (100 Hz) was utilised for all trials in this work. According to Castro et al. (2011); Debbi et al. (2012); Munoz-Organero et al. (2016), 100 Hz frequency is sufficient to record the true peak plantar pressure values during gait. Insole calibration was carried out at the participant's own body mass in the initial data gathering, based on the manufacturer's instructions. This frequency was sufficient to record the true peak plantar pressure values during gait (Ramanathan et al., 2010; Healy et al., 2012). Sensor positions were determined for each participant according to their foot size. Five pairs of insoles were utilised to accommodate varying foot sizes. Each insole consists of 960 sensing elements which can then be used to determine the average of the plantar pressure parameters (force, contact area, contact pressure, pressure time integral and peak pressure) over the ten regions of the foot, namely heel (H), midfoot (MF), first metatarsal head (1MH), second metatarsal head (2MH), third metatarsal head (3MH), fourth metatarsal head (4MH), fifth metatarsal head (5MH), hallux ($1^{st}$T), second toe ($2^{nd}$T), and third to fifth toes ($3^{rd}$-$5^{th}$T).

The in-shoe system captures plantar pressure data during foot movement and seems to be very sensitive to changes in pressure during walking. The in-shoe pressure data-acquisition system was utilised to measure the distribution of plantar pressure in all the experiments in this study. The in-shoe measurement system is preferred, and assessment of pressure at the foot-shoe interface is demanded (Cavanagh et al., 1992). The insole pressure system is shown by the presentation to be a better trade-off to do a gait analysis. The in-shoe measurement system is also capable of capturing multiple footstep data from both feet at the same time and record foot function patterns directly inside the shoe. During in-shoe recording, the participant is able to exhibit a natural walking pattern without the influence of a force plate positioned on the floor (Tekscan, 2010). The measurement system was calibrated up to 100 kPa using the F-Scan calibration device according to the manufacturer's manual. The insoles measurement system was assessed on a daily basis, before and after data collection, to ensure the accuracy of the individual sensors. The features of the F-Scan system are similar to wireless capabilities and low-profile sensors, 0.15 mm thick, pressure ranges from 345 to 862 kPa, and each F-Scan insole comprises approximately 960 sensing components (3.9 per square centimeter). The unique sensor design allows the sensor to be trimmed to fit almost any shoe, as presented in **(Figure 3.1 C and D)** (Coda & Santos, 2015; Patrick & Donovan, 2018).

This study examined the repeatability of the insole system. Ranges of pressure distribution and contact times are important parameters that can be referred to by clinicians when investigating whether the obese may develop foot pathologies. Pathological foot defects in the foot, e.g. ulcer in the diabetic foot, may cause excessive weight (loading) on certain parts of the plantar surface, and can have serious consequences for children's and adults' feet. Various foot problems and injuries are associated with these pathological feet discoveries (Dananberg, 2000; Bus et al., 2005). These foot problems and injuries are common across all sectors and ages of the community (Bus et al., 2005).

The in-shoe pressure-measuring system has previously demonstrated reliability, as shown in a study which reported a between-trial intraclass correlation coefficient (ICC) of 0.99 (McPoil et al., 2001; Vela et al., 1998). Step calibration was performed immediately prior to each participant's analysis (Coda & Santos, 2015). Each participant was calibrated using the Tekscan software while wearing the F-Scan belt, the connecting wires, the battery and finally the ankle cuff (**Figure 3.1 C and D)**.

The study initially attempted to calibrate the pressure measurements to kilopascals, an accepted unit for plantar pressure measurement (Vela et al., 1998; Patry et al., 2013). The F-Scan software accompanying the pressure measurement system was used to calibrate the sensors according to each participant's body weight prior to data collection, and record approximately six to seven steps (stances) per foot at 100 Hz for each participant. Once all walking trials were completed, plantar pressure data was saved on the computer in the laboratory then transferred to an exchangeable memory card for processing and analysis. All information was gathered and treated using the F-Scan (version 6.70) research software.


**Figure 3.1.** In-shoe pressure system (pressure sensor). (A) Flexible, thin in-shoe sensors. (B) Inserting the insole system inside the shoe (C) Represents how each participant was set up with the F-Scan system prior to each calibration and recording sensors. (D) Represents a typical plantar pressure recording obtained using the insole system, where high pressure areas can be easily identified.

### 3.2.2. Shoes

Five pairs of standard Australian men's size shoes were used. The shoe sizes of the male participants were between size 9 and size 11. The standard shoes were provided to participants when they undertook the test and were prepared by attaching an insole system to the original insole of the shoe with tape and non-slip socks (Burnfield et al., 2004) as presented in **Figure 3.1 (B)**. As mentioned earlier, footwear also has a considerable effect on plantar pressure distribution (e.g., Schaff & Cavanagh 1990; Sarnow et al., 1994; Nyska et al., 1995; Perry et al., 1995). Therefore, to minimise any effects of shoes on performance, every subject wore the same type of shoe in every experiment. In addition, the 'best-fit' insoles were carefully selected for every subject.

### 3.2.3. F-Scan software

F-Scan Research ® software is a gait analysis package that comes with the Matscan system (Tekscan). F-Scan software (Tekscan, Inc System; Version 6.70-03) was used to analyse data and evaluate the value of the pressure data for specific locations under the foot sole (Pirozzi et al., 2014). Pressure data was obtained at 100 Hz and processed as described above, as presented in (**Figure 3.2)**.

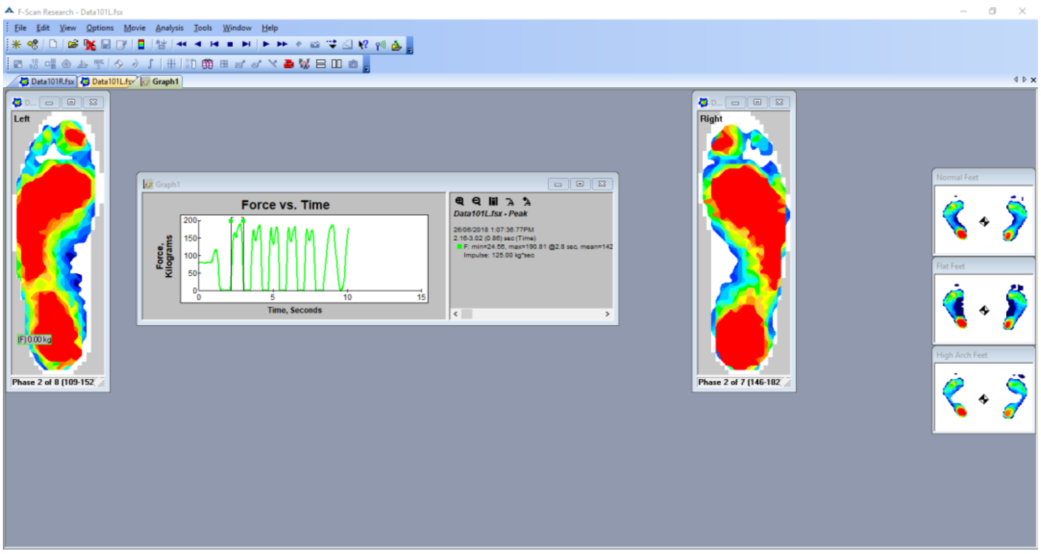



**Figure 3.2.** FScan software

3.2.4. Wall stadiometer

A portable 200 cm wall mounted stadiometer, shown in **(Figure 3.3)** was utilised to measure the participant's height in centimeters accurate to the nearest 0.1 cm (+/- 1mm).


**Figure 3.3.** Wall stadiometer

3.2.5. Body composition scanner scale

The scale is a model SC-512 health station with 160 kg /350 lb. capacity electronic scale and was used to measure body weight. This scale is easy to use and setup, as shown in (**Figure 3.4)**.


**Figure 3.4.** Body composition scanner scale

### 3.2.6. IBM SPSS statistics

The statistics software package IBM SPSS statistics (version 25) was utilised for interactive or batched statistical analysis, as indicated in (**Figure 3.5)**.

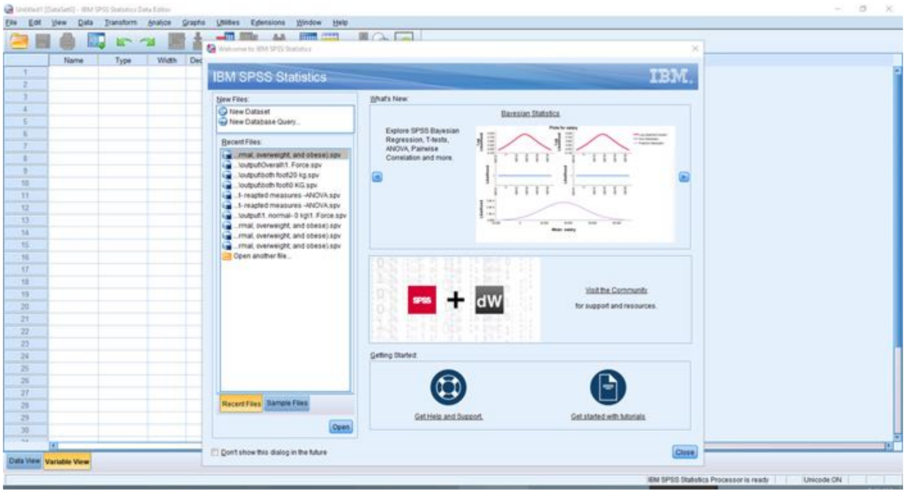



**Figure 3.5.** IBM SPSS statistics version 25

### 3.2.7. Iron mass

To modify participants' weight for simulation, nine pieces of metal weighing 3 kg with the dimensions of length, width, and thickness (26.2, 7.4 and 2 cm), respectively were used. An image of the metal is presented in (**Figure 3.6)**.

**Figure 3.6.** Show the piece of metal

### 3.2.8. Army vest.

An army vest was used to simulate body weight. It is flexible in size, so it can be fitted to every participant during testing, as shown in **(Figure 3.7)**.


**Figure 3.7.** Army vest jacket

## 3.3 University approval and experiments

### 3.3.1 Ethical approval

The experiments were carried out at the University of Southern Queensland located in Toowoomba (Queensland, Australia) during 2017 and 2018. Prior to participating in the study, each subject read and signed an informed consent form approved by the University. All data collected in this study was stored in accordance with the protocols approved through the National Statement on Ethical Conduct in Human Research out of the Research Ethics Committee (proposal number: H18REA065), and all participants freely signed an informed consent form based on the National Statement on Ethical Conduct in Human Research (2007). The informed consent form explained the purpose and the procedures of the study and that full ethics approval had been granted. The authors reported to all individuals, the steps and the process for gathering data; likewise the privacy guarantees. The subjects wore standardised footwear, and the test was organised during university hours (9:00 am-4:00 pm) and took place within a five-week period.

### 3.3.2 Ethical issues

Informed consent - All participants were aged between 24-50 years and enrolled at the university. They were sent a letter to complete and were asked to sign an assent form prior to entering the project questionnaire. The information letter included my direct phone number and subjects were asked to contact me if they had any inquiries.

Participants who consented to enrol in this study were contacted by telephone and were interviewed at a mutually convenient location. Before the test (data collection) commenced, the purpose of the research was explained, and interviewees were encouraged to ask questions if they were unsure about the test process. The interviews were recorded with the participants' consent on the basis that only I would listen to the interview and that the full written transcript of the interview would be seen only by my supervisor and myself.

Right to withdraw - Individuals who did not wish to take part in the study were asked to opt out of the study by completing and sending a message to ensure that they were not contacted again. Interview participants were informed that they did not have to answer an interview question if they did not wish and that they had the right to withdraw from the interview at any point.

Anonymity - As the main investigator, I was the only person to have access to participants' names, age, and addresses. In order to maintain participant anonymity, all questionnaires were assigned an identity number.

A copy of the **Ethical approval** and **consent forms** given to the respondents can be found in **Appendix A and Appendix B.**

### 3.3.3 Participants

All adults participating in these studies were students and staff at the University of Southern Queensland. Forty-six subjects participated in the various experiments chosen for this study. Participants were excluded from participation in the study if they disclosed a history of orthopaedic problems, suffered from pain in their feet or injury of the lower limbs, had any surgery on their feet at any time in their life, including the orthopaedic surgery patients, if they are classified as being underweight, leg length discrepancies, if they have foot abnormalities (e.g. missing toes), abnormal walking gait, any problems of balance, musculoskeletal dysfunction or any difficulties in independent locomotion neurological and/or musculoskeletal problems likely to affect their gait. Tests were initiated between June 2017 and May 2018. **Table 3.1** shows the physical characteristics of the subjects. Experiments in this study were based on previous research. The first experiment comprised fifteen adult subjects, as is reported in **Section 3.4.1**. The second experiment consisted of thirty-one participants, and the same these participants were utilised for collecting data in the third experiment, as described in **Section 3.4.2 and 3.4.3**.

**Table 3.1.** Physical characteristics of the subjects mean and SD

| Experiment | Subjects | Age (years) | | Weight (Kg) | | Height (m) | | BMI (Kg/ $m^2$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| **Exp. 1** | Fifteen subjects | 35.7 | 5.83 | 81.40 | 14.09 | 1.73 | 0.08 | 27.19 | 4.87 |
| **Exp. 2** | Thirty-one subjects | 37.5 | 6.92 | 89.82 | 17.92 | 1.74 | 0.08 | 29.7 | 5.1 |

#### 3.3.3.1 Measurements to describe the participants

The following information was collected from all participants and used to describe the universal characteristics of the research sample:

#### 3.3.3.2 Demographic characteristics for data analysis

A questionnaire that included questions about age, race, level of education, and past medical history was utilised. Properties such as age, gender, height, weight, BMI, and foot size were assessed and recorded, as well as all the participant demographics. The study participants were gathered into three groups according to their BMI values. All measuring instruments were calibrated.

#### 3.3.3.3 Height

Participants removed their shoes and stood up straight with their heels together, took a deep breath, and held it while looking straight ahead in order to ensure reliability and accuracy of their height measurement. Height was measured to the nearest 0.1 cm, utilising a portable 200 cm wall mounted height measuring tape. Height values were expressed as centimeters (WHO, 2008).

#### 3.3.3.4 Weight

Weight was measured with a digital weighing scale. Weight: body weight was measured with a body composition scanner scale (model SC-512 health station with the 160 kg capacity). The scale was kept completely still, and then the weight was reset to zero, the scale was calibrated before each participant was weighed. Participants were asked to wear light clothing only: shorts and a T-shirt, of the same type, standardised to ensure consistency of measurements for all participants. Measurements were taken prior to the test to ensure consistency of measurement. In addition, vest weight was recorded

#### 3.3.3.5 Body mass index

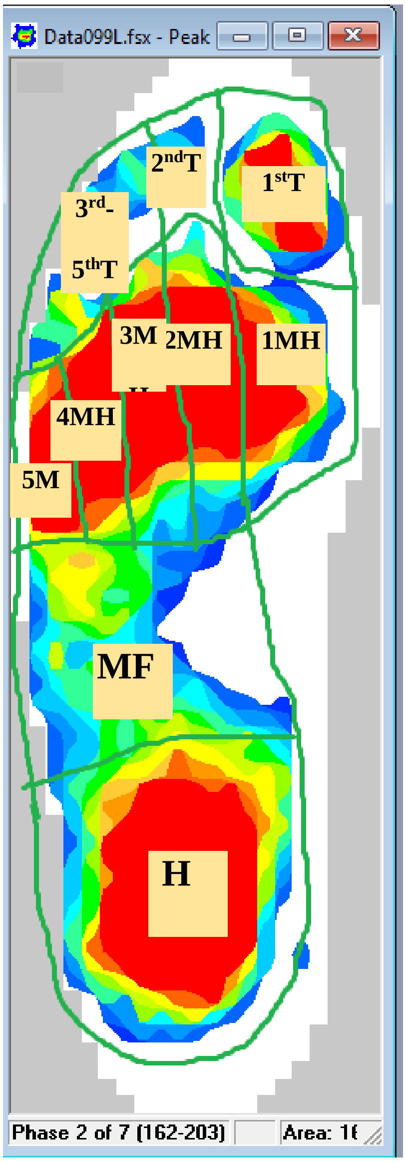
Participants were classified according to their body mass. Both height and weight were measured in accordance with standardised procedures (WHO, 2016). This information was used to calculate the body mass index (BMI) for each subject, to demonstrate their weight class based on the WHO (2016). BMI will be calculated by **Equation (3.1)**:

$$\mathbf{BMI} = \frac{\mathbf{Weight\ (Kg)}}{\mathbf{Height^2\ (m^2)}} \qquad (\mathbf{3.1})$$

#### 3.3.3.6 Dynamic plantar pressure assessment

All participants in all experiments were given time to familiarise themselves with the process of walking with the insole system to ensure they were comfortable with the procedure. Throughout data collection, all participants were encouraged to adopt a natural gait pattern and to walk at a self-selected speed. Three complete trials of the foot were recorded for each participant (Butterworth et al., 2015).

Laboratory tests (experiments **1, 2, 3)** were completed with the independent variable being body mass index. To analyse the plantar pressure distribution, the foot was partitioned in ten regions, as adapted from other studies (Xu et al., 2017; Putti et al., 2008). Within each region of interest, force, contact area, contact pressure, pressure time integral and peak pressure were obtained. The dependent variables were measures of plantar pressure (force, contact area, contact pressure, pressure time integral and peak pressure) over the ten regions of the foot, namely heel (H), midfoot (MF), first metatarsal head (1MH), second metatarsal head (2MH), third metatarsal head (3MH), fourth metatarsal head (4MH), fifth metatarsal head (5MH), hallux ($1^{st}$T), second toe ($2^{nd}$T), and third to fifth toes ($3^{rd}$-$5^{th}$T) **(Figure 3.8)**, using F-Scan software (Version 6.70-03, Tekscan, Boston, MA).




| Mask | Region |
|---|---|
| H | Heel |
| MF | Midfoot |
| 1MH | First metatarsal head |
| 2MH | Second metatarsal head |
| 3MH | Third metatarsal head |
| 4MH | Fourth metatarsal head |
| 5MH | Fifth metatarsal head |
| $1^{st}$T | Hallux |
| $2^{nd}$T | Second toe |
| $3^{rd}$ -$5^{th}$T | 3–5 Toes |

**Figure 3.8.** Plantar foot divided into ten regions

## 3.4 Experiment design

### 3.4.1 Experiment 1: foot loading pattern variations between healthy, overweight, and obese adults

Fifteen adult male participants were recruited. They were aged between 25-46 years. Adults were excluded from participation in the study if they disclosed a history of orthopaedic problems, any disorder of balance, musculoskeletal dysfunction or any discomforts in the independent movement, neurological and/or musculoskeletal problems likely to affect their gait. The participants were divided into three categories of healthy weight (BMI <25), overweight (25< BMI <30), and obese (BMI >30) as displayed in **(Figure 3.9)**. Participants were grouped according to BMI, and by following similar protocols to those used with children and adults, as described by Filippin et al. (2007); Hills et al. (2001); Pirozzi et al. (2014); three groups were obtained for comparison. Participant demographics are presented in **Table 3.2**.

Testing protocols for the first experiment were as follows. The protocol for the assessment of plantar pressure in this experiment was the three-step method with three trials. The plantar pressure insole was calibrated for each subject. In each category, three valid trials were collected for each foot, as this number of trials has previously been found to be sufficient to ensure adequate reliability of force and pressure data (van der Leeden et al., 2004; Hughes et al., 1991). The average of the three measurements was used to describe the range of motion of the ankle, subtalar, and first metatarsophalangeal joints for each subject (Arndt et al., 2004; Leardini et al., 1999). Participants were admitted for ten minutes where they could practice gait at a self-selected velocity with an insole system. Walking speed was not controlled because, although a prescribed walking speed might help to compare the pressure manners of various participants, it would stop the generation of a normal walking manner. In addition, using a metronome might cause an atypical step (Rosenbaum and Becker, 1997; Monteiro et al., 2010). All participants were asked to walk along a five-metre walkway with an insole system that was attached to the participants' shoes as shown in **(Figure 3.1(C)**.

**Table 3.2.** Participant information for each of the three groups of participants (Experiment 1)

| Group | N | Age (years) | | Height (m) | | Weight (kg) | | BMI ($Kg/m^2$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| **Healthy** | 5 | 35.40 | 6.35 | 1.78 | 0.09 | 69.42 | 7.48 | 21.88 | 1.26 |
| **Overweight** | 5 | 36.20 | 4.76 | 1.68 | 0.05 | 76.12 | 6.61 | 26.82 | 1.60 |
| **Obese** | 5 | 35.4 | 7.4 | 1.7 | 0.1 | 98.7 | 2.9 | 32.9 | 1.7 |


**Figure 3.9.** Participants were grouped within three categories based on their BMI: (A) healthy, (B) overweight, and (C) obese

### 3.4.2 Experiment 2: simulation body weight protocol and determination of plantar pressure

An experimental design using subjects and repeated measures were employed for this study. This research was in a laboratory environment and exploratory in nature. The participant was chosen among the suitability of students and staff. The participants of this study were limited to 24 to 50 year old adults and comprised thirty-one adult males. The mean of all following features were gathered: age 37.55±6.92 years, height 1.74±0.08 m, the body mass 89.82±17.92 kg and BMI 29.7±5.1 kg/$m^2$. Healthy was defined as free of cardiac and/or neurological problems, such as arrhythmia, heart attack, or stroke, and free of any musculoskeletal or pathological problems (osteoarthritis, bone fractures or shin splints). Participants did not have a history of major lower extremity injury and/or surgery within the last year. These conditions were screened using a medical-history form.

In this experiment, the author replicated the basic structure of a previously published study design investigating the effects of increasing weight on peak plantar pressures (Vela et al., 1998) but with modification in terms of the changes of added mass (simulation body weight protocol); all the subjects wore jackets. That study had added (9.1 and 18.1) kg to asymptomatic participants wearing normal shoes, without reference to the particular BMI or weight.

Testing protocol for the second experiment adhered to protocols for the assessment of plantar pressure in adults previously used in a laboratory (Ramachandra et al.,2012) because the three-step gait protocol showed enhanced reliability to measure the walking and plantar pressure pattern compared with the one step gait protocol and the midstance protocol. It was decided that the best protocol to use for this investigation was the three-step method. The participants continued to walk ten metres while looking straight ahead until three valid trials were captured bilaterally. In each condition, three valid trials were collected for each foot, as this number of trials has previously been found to be sufficient to ensure adequate reliability (AL-Baghdadi et al., 2011; Barisch-Fritz et al., 2014; Ramachandra et al., 2012; van der Leeden et al., 2004; Yan et al., 2013; Yan et al., 2014; Yan et al., 2016). Once all walking trials were completed, plantar pressure data was saved on the computer in the laboratory then transferred to an exchangeable memory card for processing and analysis. Mean values of the foot measures were calculated across the three trials for each foot (Arndt et al., 2004; Leardini et al., 1999); each trial consisting of an average of the three-step method over ten meters. The plantar pressure insole was calibrated for each subject.

Participants were provided with standard shoes when they undertook the test, prepared by attaching an insole system to the original insole of the shoe with tape and non-slip socks (Burnfield et al., 2004). Each participant was calibrated using the Tekscan software while wearing the FScan belt, the connecting wires, the battery and finally the ankle cuff. All information was gathered and treated using the F-Scan (version 6.70) research software. Plantar pressure data was obtained at 100 Hz and processed as described. The frequency (100 Hz) was utilised for all trials in this work. 100 Hz frequency is satisfactory to record the true peak plantar pressure values during gait (Ramanathan et al., 2010; Healy et al., 2012).

The pressure data collection protocol involved pressure measurements with an additional four separate loading conditions (0, 10, 20, and 30 kg of iron mass respectively). To ensure that participants felt as comfortable as normal with the increase in body weight, each subject acted as their own control. Loading conditions to simulate an increase in body mass were achieved with the application of a weighted vest. Subjects completed each walking trial on a 10-meter walkway. As we added weight, we tried as much as possible to distribute the weights equally between the front area (chest) and the back area (back) in order to simulate and obtain a weight tolerance for normal weight gain as shown in **(Figure 3.10)**.

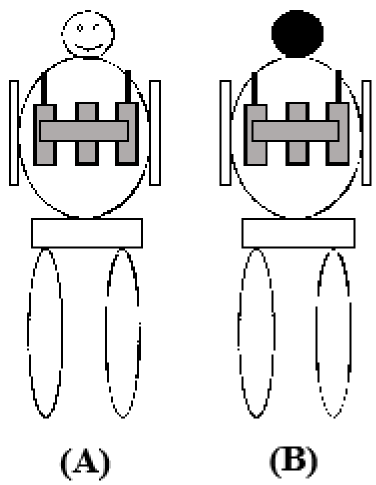



**Figure 3.10.** Modification of volunteer body weight by adding weight evenly distributed anteriorly and posteriorly using vests. State one walk without any additional weight; state two (10 kg); State three (20 kg); State four (30 kg): (A) Front view, (B) Back

For each participant, the weight was raised from a range of variance BMI (20-46.4) kg/m$^2$ with the vest included, and then filled with iron bars and fixed in the central area of each subject. The mass placed inside the vest ranged from 10 to 30 kg (mean mass = 20 ± 10 kg). Normal walking was performed for 20-minute sessions with subjects wearing the vest type mass of a 10 kg, 20 kg and 30 kg external load (loaded walking) (Lee et al., 2008). The participants wore the jacket then attached shoulder straps and two side straps so that it did not obstruct any upper or lower body moves. Three trials were repeated in each simulation condition. However, the first trials were considered as practical sets to attain a physiological steady state, and only the rest of the three trials were analysed. Later, the subjects wore the jacket and walked the same way as mentioned earlier.

### 3.4.3 Experiment 3: profiling the centroid of the area of contact captured

The same thirty-one adult male subjects who were used in experiment two, were used for collection of centroid data in experiment three. Only adults who possessed a neutral foot position were involved, although subjects who had similar foot arch features were recruited to participate in the experiment. The participants had what could be considered a normal (AHI = 0.328 ± 0.022 mm) foot arch as determined by a musculoskeletal physiotherapist (Roposh, 2010). All the participant demographics are presented in **Table 3.3.**

**Table 3.3.** Participant characteristics of the study population

| | **N** | **Age (years)** | | **Height (m)** | | **Weight (kg)** | | **BMI (Kg/m$^2$)** | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| **Subject** | 31 | 37.55 | 6.92 | 1.74 | 0.08 | 89.82 | 17.92 | 29.7 | 5.1 |

Prior to the experiment, the F-Scan sensor sheets were tailored to make sure they had the same shape and size as the instrumented insoles. They were then pasted underneath the instrumented insoles; it was then noted that the instrumented insole was placed in between the foot and F-Scan sensor sheet, as shown in **(Figure 3.1, A & B)**. The procedure was similar to experiment two. The participants were instructed to practice a three-step gait. When the subjects were confident, their gait was recorded. And the recording of centroid data in each three-foot position (heel strike, midstance, and toe-off) were divided according to the weight added. Next, each participant performed three sets of three steps, which were repeated with each weight that was attached to the participant's body. Normal walking was performed for 20-minute sessions.

An innovative technique for the calculation of the centroid of the area of contact captured by the system was developed, with a reference line on every plantar pressure pedograph (Pataky et al., 2008; Chong & Milburn, 2017), which is also introduced in this section. The centroid of the area of contact with the surface is located by calculating the geometric centre of a set of cloud points having the lowest z coordinate value as shown in **(Figure 3.11)**. In this case, the z value is the surface height of the insole measurement system and is equal to 0.0 mm. A modified version of the algorithms developed by Yu et al. (2007) is used in the centroid calculation. Generally, a centroid position can be calculated for every computed between foot strike and toe-off. The method may be used to determine the centroid of the plantar surface at any z value or a range of z values.

$$\boldsymbol{X_C = 0.0 = \frac{\sum_{i=1}^{N} Xi}{N}} \qquad (3.2)$$

$$\boldsymbol{Y_C = 0.0 = \frac{\sum_{i=1}^{N} Yi}{N}} \qquad (3.3)$$

In this case, the z value is the surface height of the insole measurement system and is equal to 0.0 mm. *xc* and *yc* are the centroid coordinates, and *xi* and *yi* are the coordinates of the individual points in a cluster of point clouds during the three-step method within three trials. In this part, a foot pressure sensing insole has been used to calculate the moment of heel strike, midstance and the toe-off phases by using F-Scan software (Version 6.70-03, Tekscan, Boston, MA), as shown in **(Figure 3.11)**.

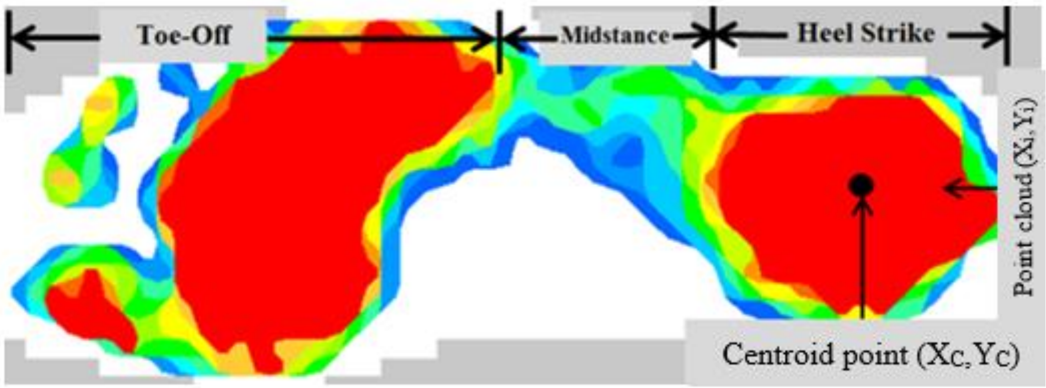



**Figure 3.11.** Determining the centroid of the heel strike during gait. The one-step sequence of gait cycle phases which start from heel strike, midstance and toe-off phases.

## 3.5 The method used in data analysis

All data was analysed using statistical software (SPSS version 25.0). Statistical significance was accepted at the $P < 0.001$ level of confidence.

### 3.5.1 The coefficients of variation:

The repeatability coefficient (CR) is a precision measure which represents the value below, which is the absolute difference between two repeated test results that may be expected to lie with a probability of 95% (Hopkins, 2000; Chong, 2016; Putti et al., 2008). The analysed variables for gait are measured in each selected area during stance; the CA is determined by the sum of the area of all overloaded sensors within an area (Putti et al., 2008; Chong, 2016). The CR is calculated using SD/mean multiplied by 100, as in the equation below:

$$\mathbf{CV = SD/mean \times 100\%} \qquad \mathbf{(3.4)}$$

### 3.5.2 Analysis of variance

Analysis of variance (ANOVA) is a statistical method utilised to verify the significance of the differences between the averages of three or more groups in a single dependent variable. It is intended to compare averages or to arrive at a decision about whether there are differences between the performance averages of groups that have been subjected to various processes to arrive at agents that make some means different from other means.

### 3.5.3 Intra-class correlation coefficients

Intraclass correlation coefficient (ICC) methods have been widely utilised for estimating or evaluating the quantitative measurements obtained by different raters or assessors. According to Donner and Koval (1980), reliability is the extent of the consistency or stability of measurement that exposes the steadiness in the repeated measurement to the same subject under identical conditions. Therefore, a reliable test can be obtained if the random error or unsystematic variation in measurement in the repeated measurements is minimal. A number of statistical approaches are employed to describe the reliability of the measured data. ICC is normally utilised in assessing the quantitative measurements obtained by different rates or assessors. Typically, the magnitude of ICC ranges between zero and one. A perfect agreement between assessors happens if the value of the ICC approaches one, whereas an imperfect agreement between the assessors occurs if the ICC value approaches zero. Currently, ICC has been commonly used in conservative care medicine to evaluate inter-rater, test-retest, and intra-rater reliability (Cramer et al., 2010; Owens et al., 2004; Koo et al. 2011; Houweling et al., 2014; Clare et al., 2003; Battaglia et al., 2014; Leach et al., 2003; Russell et al., 2012; Koo & Li, 2016). See below for definitions of each estimate:

- Interrater reliability considers the differences amidst two or more raters measuring the same set of participants.
- Test-retest reliability must invert the differences in assessments taken via an instrument on the same participant under the same situations. It is normally indicative of reliability in conditions when raters are not involved, or rater impact is negligible, like a self-report survey instrument.
- Intrarater reliability considers the different data measured by one rater across two or more trials.

There are various types of ICC published literature has classified ICC into three different classes (field, 2005) depending on model and form of ICC, which are presented in **Table 3.4.**

**Table 3.4.** Different cases for calculation ICC depending on model and form of ICC

| ICC type | Description |
|---|---|
| ICC(1,1) | Each subject is assessed by a different set of randomly selected raters, and the reliability is calculated from a single measurement. Uncommonly used in clinical reliability studies. |
| ICC(1,k) | As above, but reliability is calculated by taking an average of the k raters' measurements. |
| ICC(2,1) | Each subject is measured by each rater, and raters are considered representative of a larger population of similar raters. Reliability is calculated from a single measurement. |
| ICC(2,k) | As above, but reliability is calculated by taking an average of the k raters' measurements. |
| ICC(3,1) | Each subject is assessed by each rater, but the raters are the only raters of interest. Reliability is calculated from a single measurement. |
| ICC(3,k) | As above, but reliability is calculated by taking an average of the k raters' measurements. |

ICC estimates and their 95% confidence intervals were calculated using SPSS statistical package version 25. The following boundary conditions were used with respect to the ICC: 0.75 and 0.90 limits for good to excellent or a high or good reliability (Youdas et al., 1991; Portney & Watkins, 2015), 0.5 and 0.75 moderate reliability, and less than 0.5 poor reliability (Watkins & Portney, 2009).

These evaluations are essential to clinical assessments because without them, we would have no confidence in their measurements, nor could they draw any rational conclusions from their measurements (Koo & Li, 2016). ICC statistical techniques are used to evaluate the reliability among several measurements. Different cases for calculating ICC depending on models vary depending on types of trials (judges) and targets (subjects). Based on Shrout and Fleiss (1979), the cases of ICC, the study used a full factorial design with two independent variables. Namely, ten-foot regions, and simulated body weight. Each participant received the same four conditions, walk without weight and simulated with three different weights (10, 20 and 30 kg). Additionally, the ICC for each measure in each condition were calculated to investigate its reliability using SPSS. The ICC formula is shown below:

1. Model 1: each subject is assessed by a different set of randomly selected raters, one-way random effects model and form:

$$\textbf{ICC (1, K)} = \frac{BM_S - WM_S}{BM_S} \qquad \textbf{(3.5)}$$

Where, BMS is the between-subjects mean square from the analysis of variance, and WMS is the within-groups (error) mean square. K is the number of ratings for each subject.

2. Model 2: each subject is assessed by each rater and raters are randomly selected, two-way random effects model and form:

$$\textbf{ICC (2, k)} = \frac{BM_S - EM_S}{BM_S + \frac{RM_S - EM_S}{n}} \qquad \textbf{(3.6)}$$

Where: EMS is the error mean square, RMS is the between-raters mean square, k is the number of raters, and n is the number of subjects tested.

3. Model 3: each subject is assessed by each rater, but raters are the only items of interest, two-way mixed model and form:

$$\textbf{ICC (3, k)} = \frac{BM_S - EM_S}{BM_S} \qquad \textbf{(3.7)}$$

For this dissertation, **Model 2** is used to calculate the reliability of gait variables since it is a repeated measures method. In addition, the sample size requirements are computed based on the ICC values. Detailed results will be introduced **in chapter 5, sections 5.2.**

## 3.6 Analysis of experiments

### 3.6.1 Analysis of experiment 1

The statistical procedures were done using the SPSS statistical package (version25; SPSS Inc, Chicago, IL, USA). Area analyses involved 10 anatomical regions which were calculated by the F-Scan software **(Figure 3.2)**. The mean of the three repetitions for each subject was computed, and all the statistical procedures were performed with these mean values. Mean and standard deviations (SD) were calculated for each variable. A one-way within subject repeated measures analysis-of-variance (ANOVA) model was utilised to consider whether there were significant differences in the parameter for the groups with obese, overweight and normal weight conditions, with and without variation in BMI. This was used to test for significant differences in plantar loading. These were done on each of the dependent variables with categories of healthy and obese, as the independent variable (Kunter et al., 2005). Where differences existed between groups, Tukey post-hoc tests were used to compare variables and to ascertain the location of the difference between the three groups for both feet. The level of significance was set at $P < 0.01$.

### 3.6.2 Analysis of experiment 2

The data was collected and analysed. The results were expressed as mean ± SD values, and presented in the format of mean (SD). The SD of the between data differences identified in the ANOVA were used to determine the coefficient of repeatability (CR) of each parameter (Bland & Altman, 1986). This was expressed as a percentage of the mean by using the formula [(CR)/mean] - 100, i.e., the lower the CR, the stronger the repeatability (Putti et al., 2008). Repeatability of the three trials for each left and right foot, was calculated separately, and these values were used to calculate the mean CR for all measures. Data was tested for outliers and summarised using descriptive statistics. The methods of Bland and Altman (1986) were used to assess repeatability. As suggested by Hopkins (2000), CR was used to calculate the repeatability. Then the data was exported into Microsoft Excel 2016. Descriptive statistics were reported in terms of the mean, SD, range, and percentage of increases and decreases. The level of statistical significance was set at the ($P \leq 0.05$) level.

Variability in the data will be assessed via the calculation of coefficients of variation; this analysis of absolute reliability provides information regarding within-trial variability expressed as a percentage (with the associated P-values), based on the General Linear Model. CR expresses the typical error as a percentage of the mean and is defined as (SD/mean)×100. The higher the CR value, the weaker the repeatability. The differences between the measurements over two occasions and the averages from the trials were calculated to test repeatability. Using the F-Scan software, the foot was divided into ten areas and the five most clinically relevant parameters for both feet were assessed. Measurements from both feet were analysed separately for repeatability. These accounted for 100 evaluated variables.

Data was not normalised for foot size and weight. The standard deviation reflects within subject and between subject variations as well as trial-to-trial differences and variation in the in-shoe system (Gurney et al., 2008). For all participants left foot and right foot data of three trials were combined, which was assessed using the reliability of ICC. The size of the variations within these trials was reported as a CR. The intra-individual repeatability for the variables and duration of stance phase was verified by means of ICC, since the difference in results between test weights was random (Cavanagh & Ulbrecht, 1994; Wearing et al., 1999). The mean of the three trials of each subject was computed and all the statistical procedures were performed with these mean values.

### 3.6.3 Analysis of experiment 3

The data was collected and analysed. The results were expressed as mean ± SD values, and presented in the format ‘mean (SD)’ for this experiment. The x-axis and y-axis coordinates can be shown by other methods, which include mean and standard deviation by recording three walks with 31 participants at the normal walking speed. The information was arranged in mean and standard deviation formats, considering the values of three steps each day, for each foot.

## 3.7 Assumptions

The following assumptions were made in this study:

1. Participants understood and followed the instructions closely;

2. Walking speed was not tested during this investigation because it was assumed that everybody's walk is normalised, therefore, all walk patterns should be the same between trials;

3. Participants were comfortable wearing the footwear provided;

4. The setting, a typical gait lab, did not influence gait pattern significantly.

## 3.8 Chapter summary

This chapter focused on the equipment, participants, procedures and inputs used in the search to collect data and provide access to the results related to the subject of research. The main conclusions derived from **chapter 3** are summarised below:

- Participants' properties were measured (height, weight, and BMI).
- Plantar pressure of the foot was collected, and data recorded by using the insole system.
- All data were identified and analysed.

The following chapters (chapter 4, chapter 5 and chapter 6) present the finding from the first, second and third studies for each of the three research objectives. The next chapter (chapter 4) begins with the findings of objective 1.

# 4. RESULT OF EXPERIMENT 1

## 4.1 Introduction

This chapter exhibits the outcomes that answer objective one, which studied the effect of differences in body mass (healthy, overweight and obese) in adults aged between 25 and 46 years and the associated effects on plantar pressure distribution characteristics by calculating the foot force, contact area, contact pressure, peak pressure and pressure time integral to different foot regions during gait, using the in-shoe system. There are six main sections in this chapter: experiment details, force and contact area results, contact pressure and pressure time integral results, peak pressure outcomes, discussion of results and the chapter summary.

The three groups (five people in each group) of adult male participants were recruited into the study. Division of these groups was based on participants' body mass and BMI: normal weight, overweight and obese. The subjects were between 25 and 46 years of age, and the BMI rate obtained for obese adults (32.9 kg/m$^2$) was significantly higher ($P < 0.001$) than that of the healthy group (21.88 kg/m$^2$). To study the effect of differences in the body mass of adults on plantar pressure distribution characteristics (calculating foot force, contact area, contact pressure, peak pressure and pressure time integral to different foot regions during gait) an in-shoe system was used. The characteristics are shown in **Table 3.2**.

### 4.1.1. Force and contact area measurements

Descriptive data for force (F, N) and contact area (CA, cm$^2$) is shown in **Table 4.1**. There was a statistically significant variation ($P < 0.001$) into the F measure. The lower differences in mean F measured value was located at the 3$^{rd}$–5$^{th}$T and 2$^{nd}$T between normal weight and overweight. The mean value for F within these groups at the 3$^{rd}$–5$^{th}$T were 6.21 N and 14.24 N, respectively. Moreover, the mean value for F under the 2$^{nd}$T were 7.53 N and 10.82 N within healthy, and overweight, respectively. Moreover, the biggest mean values of the F as appears in **Table 4.1,** was under the obese category followed by the overweight group compared with the healthy group, which were 91.70 N, 69.87 N to 55.31 N.

**Table 4.1.** Summary of the dynamic force (N) and contact area ($cm^2$) data for the normal weight (n=5), overweight (n=5) and obese (n=5) [Mean (SD) of three trials]

| | **Force (N)** | | | | | | | **Contact area ($cm^2$)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | Healthy | | Overweight | | Obese | | | Healthy | | Overweight | | Obese | |
| | Mean | SD | Mean | SD | Mean | SD | | Mean | SD | Mean | SD | Mean | SD |
| **$3^{rd}$-$5^{th}$T** | 6.21 | 6.74 | 14.24 | 8.90 | 14.99 | 8.38 | | 0.74 | 0.26 | 1.17 | 1.01 | 1.37 | 0.15 |
| **$2^{nd}$T** | 7.53 | 5.53 | 10.82 | 7.18 | 12.32 | 7.84 | | 0.81 | 0.35 | 0.83 | 0.70 | 0.84 | 0.45 |
| **$1^{st}$T** | 45.29 | 36.54 | 58.39 | 28.01 | 103.37 | 41.64 | | 3.21 | 1.43 | 2.99 | 1.33 | 4.77 | 1.82 |
| **5MH** | 26.06 | 15.91 | 31.02 | 15.10 | 37.69 | 19.46 | | 2.57 | 1.44 | 2.87 | 1.37 | 3.16 | 1.38 |
| **4MH** | 34.79 | 18.27 | 39.63 | 14.91 | 63.65 | 26.17 | | 3.08 | 1.50 | 3.42 | 1.07 | 4.57 | 1.31 |
| **3MH** | 42.99 | 20.51 | 56.13 | 28.95 | 81.33 | 23.20 | | 3.56 | 1.63 | 4.06 | 0.91 | 5.27 | 1.23 |
| **2MH** | 49.50 | 20.62 | 69.05 | 29.29 | 98.01 | 25.30 | | 3.44 | 1.64 | 4.23 | 0.93 | 5.81 | 1.37 |
| **1MH** | 70.41 | 35.11 | 102.62 | 40.12 | 142.49 | 35.14 | | 6.15 | 2.80 | 7.20 | 1.78 | 9.41 | 2.54 |
| **MF** | 40.31 | 20.40 | 45.87 | 21.69 | 62.61 | 25.60 | | 3.68 | 1.14 | 4.90 | 2.64 | 7.88 | 2.49 |
| **H** | 230.00 | 69.82 | 270.90 | 93.08 | 300.52 | 121.63 | | 15.55 | 4.47 | 16.53 | 5.72 | 17.88 | 6.21 |
| **Mean** | 55.31 | | 69.87 | | 91.70 | | | 4.28 | | 4.82 | | 6.10 | |

Statistically significant differences were found between the obese adults group and normal weight adults group in the following regions with mean values for F measure (P-values <0.001) at the H was 300.52 N, 1MH was 142.49 N, followed by the $1^{st}$T and 2MH with mean value 103.37 N and 98.01 N, respectively. In contrast, the mean values of the F variable in the obese group were approximately twice that under the 1MH with 142.49 N, $1^{st}$T with 103.37 N and 2MH with 98.01 N in contrast with the healthy group with values of 70.41, 45.29 and 49.50 N, at the same foot area. It was observed that the average values of the F measure under the whole foot and BMI for these three groups, shown in (**Figure 4.1)**.

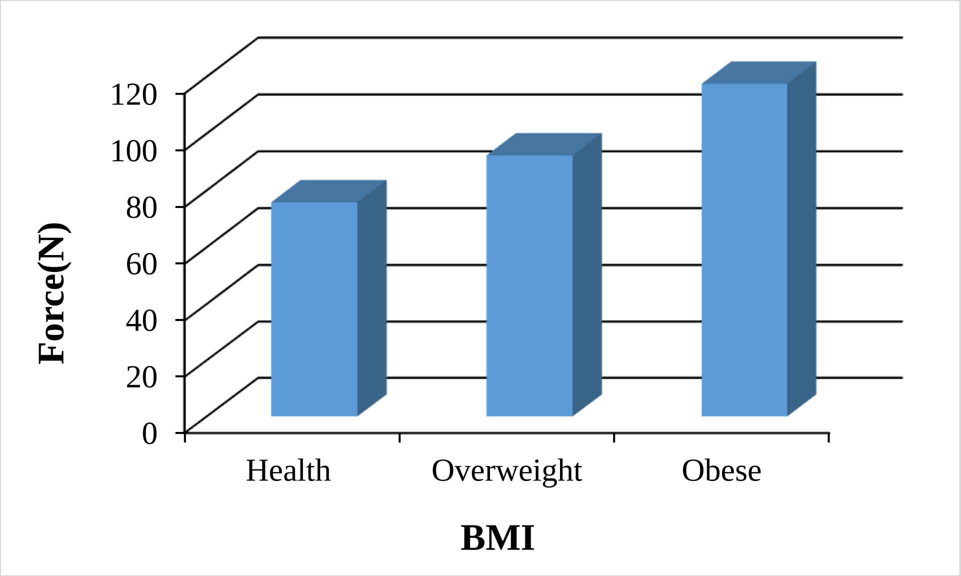



**Figure 4.1.** The relationship between force (N) measure and BMI (kg/m²)

Illustrative data for CA ($cm^2$) measures in the adults who were obese, overweight and normal weight is seen in **Table 4.1**. In general, there were statistically significant differences (P-values <0.001) for the CA. The lower differences for the CA measure was located at the $3^{rd}$–$5^{th}$T and $2^{nd}$T between the normal weight, overweight and obese adults. The mean values for CA under $3^{rd}$–$5^{th}$T were 0.74 $cm^2$, 1.17 $cm^2$ and 1.37 $cm^2$, respectively. Whereas the mean CA measure under the $2^{nd}$T were 0.81 $cm^2$, 0.83 $cm^2$ and 0.84 $cm^2$, respectively. The higher CA value was found to be within the obese then overweight category compared to the normal category.

The overweight category presented greater CA than the normal weight adults of the same age, these differences were located beneath the H with 16.53 $cm^2$, 1MH with 7.20 $cm^2$, MF with 4.90 $cm^2$ followed by 2MH with 4.23 $cm^2$ and 3MH with 4.06 $cm^2$, regions. Whereas in the healthy group CA was 15.55, 6.15, 3.68, 3.44, and 3.56 $cm^2$. The obese group had higher foot CA values in comparison with the control group, under the H, 1MH and MF regions with the values 17.88, 9.41 and 7.88 $cm^2$, respectively. Thus, all values were higher within the obese group. **Figure 4.2** presents the relationships detected between the CA measurements within the whole foot regions within these three groups (according to their BMI), displaying a higher mean value beneath the obese category.

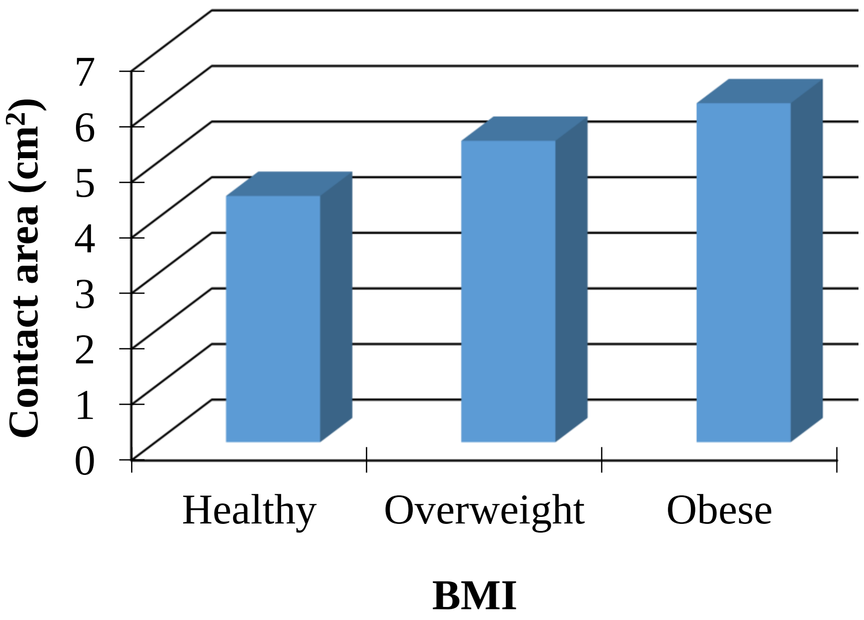



**Figure 4.2.** The relationship between the contact area ($cm^2$) measure and BMI ($kg/m^2$)

Post-hoc analysis using the Tukey's honestly significant difference test, confirmed that the obese group had a significantly higher mean dynamic force of 117.52 N in comparison with the overweight group of 92.30 N and the normal weight group of 75.82 N. Furthermore, the obese subjects displayed a notably higher mean contact area of 7.78 $cm^2$ than the normal subjects of 6.14 $cm^2$ and the overweight group of 6.51 $cm^2$.

### 4.1.2. Contact pressure and pressure-time integrals

A consistent increase in overall foot loading data for contact pressure (CP, kPa) and temporal characteristics of foot loading pressure–time integrals (PTI, kPa/s) for the groups are summarised in **Table 4.2**. There were notable variances between all three categories within CP and PTI measures which were observed at ($P < 0.001$).

The greater CP values were measured under the 2MH, H, 3MH, $1^{st}$T and 1MH regions in the obese group compared with the normal group. These regions had mean CP values in the obese group of 118.96, 115.42, 111.27, 103.84 and 100.81 kPa, respectively. Whereas, these regions had mean CP values in the healthy group of 69.98, 90.20, 68.14, 55.38, and 61.53 kPa, respectively. The highest CP was under the MF in the obese group and the mean 85.58 kPa, which was approximately twice that under the same region in the normal group had a mean of 42.86 kPa. In addition, the obese group presented roughly double the value under the $1^{st}$T zone with a mean value of 103.84 kPa compared to the healthy category of 55.38 kPa.

There was a small dissimilarity amidst the overweight and normal weight groups for CP located at H with 98.98 kPa, 2MH with 84.67 kPa, $1^{st}$T with 83.82 kPa and 3MH with 80.68 kPa. In the normal group the CP values were 90.20, 69.98, 55.38 and 68.14 kPa respectively under the same foot area. On the other hand, the lowest CP value was observed within $3^{rd}$-$5^{th}$T and $2^{nd}$T regions with the mean value for overweight of 37.65 and 42.11 kPa and healthy groups of 26.32 and 30.89 kPa. It was observed that the greater mean values of the CP measure under the whole foot and body mass index within these three groups, are shown in **(Figure 4.3)**.

**Table 4.2.** Summary of the contact pressure (kPa) and pressure–time integral (kPa/s) data for the healthy weight (n=5), overweight (n=5) and obese (n=5) [Mean (SD) of three trials]

| Foot region | Contact pressure (kPa) | | | | | | Pressure time integrals (KPa s) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Healthy | | Overweight | | Obese | | Healthy | | Overweight | | Obese | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| **$3^{rd}$-$5^{th}$T** | 26.32 | 11.49 | 37.65 | 15.75 | 34.01 | 28.50 | 28.34 | 15.92 | 37.04 | 11.42 | 58.76 | 14.96 |
| **$2^{nd}$T** | 30.89 | 14.32 | 42.11 | 15.22 | 52.67 | 10.41 | 34.58 | 12.20 | 44.62 | 10.97 | 82.59 | 19.65 |
| **$1^{st}$T** | 55.38 | 15.32 | 83.82 | 19.30 | 103.84 | 56.92 | 57.31 | 23.96 | 90.81 | 26.60 | 116.63 | 17.38 |
| **5MH** | 52.80 | 12.86 | 62.97 | 24.58 | 75.91 | 43.70 | 61.14 | 25.33 | 65.97 | 18.04 | 74.10 | 38.73 |
| **4MH** | 63.86 | 17.76 | 73.77 | 32.13 | 97.32 | 45.81 | 70.77 | 23.60 | 78.33 | 27.72 | 96.25 | 42.16 |
| **3MH** | 68.14 | 16.52 | 80.68 | 27.11 | 111.27 | 34.20 | 77.95 | 30.41 | 83.80 | 21.38 | 100.02 | 41.21 |
| **2MH** | 69.98 | 17.54 | 84.67 | 25.44 | 118.96 | 31.34 | 84.57 | 27.32 | 93.64 | 20.27 | 109.65 | 53.41 |
| **1MH** | 61.53 | 19.52 | 70.90 | 26.04 | 100.81 | 27.33 | 70.82 | 28.14 | 86.56 | 24.56 | 101.12 | 40.76 |
| **MF** | 42.86 | 16.44 | 50.93 | 15.20 | 85.58 | 38.21 | 35.21 | 14.65 | 49.94 | 11.80 | 58.21 | 14.71 |
| **H** | 90.20 | 22.75 | 98.98 | 25.95 | 115.42 | 61.73 | 93.54 | 28.91 | 116.00 | 71.96 | 123.24 | 60.36 |
| **Mean** | 56.20 | | 68.65 | | 89.58 | | 61.42 | | 74.67 | | 92.06 | |

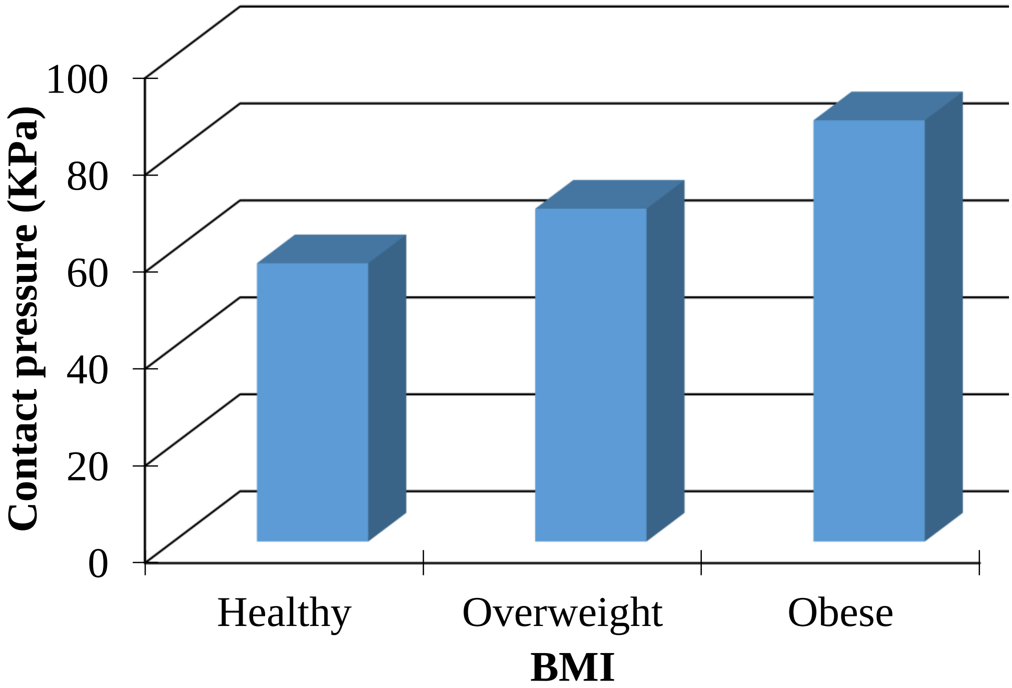



**Figure 4.3.** The relationship between contact pressure (KPa) measure and BMI (kg/m²)

Elevated PTI were attributed to the smallest level of probability the Tukey's honestly significant difference test, for the PTI for these groups. The normal weight group was with 61.42 kPa/s, followed by the overweight with 74.67 kPa/s and the obese group with 92.06 kPa/s. The results show higher PTI value underneath the H, 1stT, 2MH and 3MH in the obese group ($P < 0.001$) compared to the healthy category. The obese category had mean values under the H, 1stT, 2MH and 3MH regions with 123.24, 116.63, 109.65, 100.02 kPa/s, respectively.

The overweight group PTI also was higher compared with the healthy group beneath the H, 2MH, 1stT and 1MH regions, with mean values of 116.00, 93.64, and 90.81, 86.56 kPa/s. While, the healthy group had mean values of 93.54, 84.57, 57.31 and 70.82 kPa/s, within these regions respectively. On the other hand, the lowest region within this PTI measure was absorbed under 3rd-5thT with 58.76 and 37.04 kPa/s for both groups ($P < 0.001$) compared with the normal weight group with 28.34 kPa/s, is shown in **Table 4.2**. It was observed that the a higher mean values of the PTI measure under the whole foot and body mass index within these three groups, as shown in **(Figure 4.4)**.

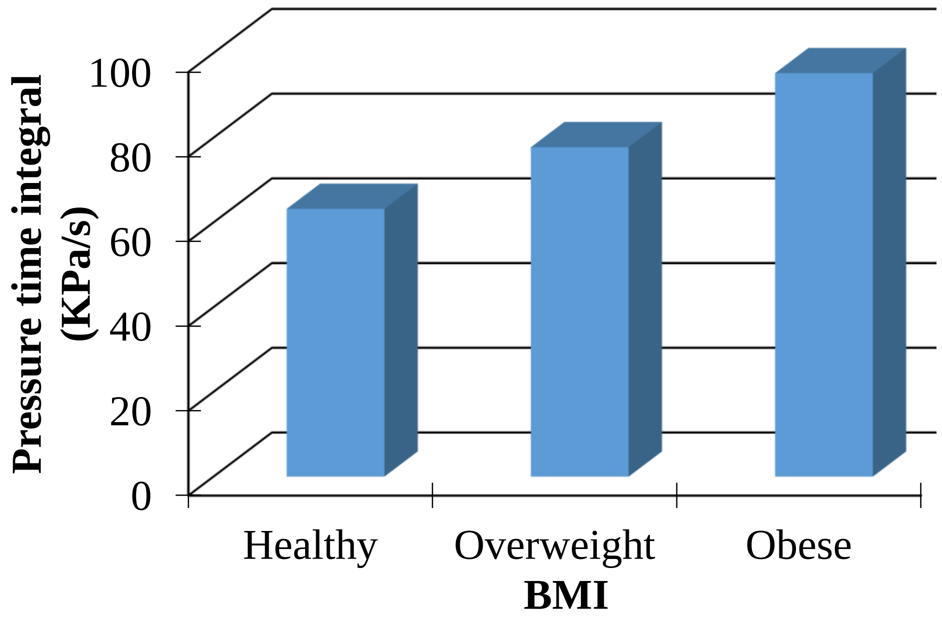
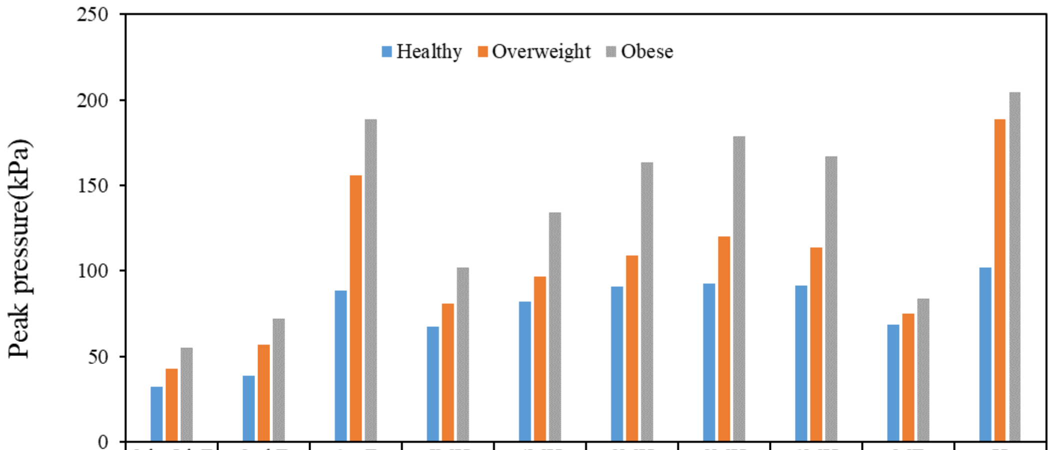



**Figure 4.4.** The relationship between pressure time integral (kPa/s) measure and BMI (kg/m²)

4.1.3. Peak pressure

The peak pressure (PP) was generally higher in the obese group compared with the other two groups. The highest PP obtained in the obese group under the H with 204.38 kPa followed by the 1$^{st}$T with 189.00 kPa. Descriptive data for the maximum and minimum PP in healthy, overweight and obese groups are represented in **(Figure 4.5)** while the obese category was likened to both the overweight and healthy groups. The PP value had a maximum variance within the obese group at both regions of H with 204.38 kPa and the 1$^{st}$T with 189.99 kPa, which approximately double those of the healthy group with 101.71 and 88.37 kPa respectively. The lowest value, in contrast, was under the 3$^{rd}$-5$^{th}$T and 2$^{nd}$T, which was the lowest change between these three groups (obese, overweight and healthy) under these regions. The mean PP values for these region were 55.36, 42.62 and 32.20 kPa; and 72.13, 56.73 and 38.89 kPa, respectively within the same area. It was found to be greater than both groups (overweight and healthy) as displayed in **(Figure 4.5)**, which shows the comparisons between the healthy, overweight and obese groups.




| | 3th–5th T | 2nd T | 1st T | 5MH | 4MH | 3MH | 2MH | 1MH | MF | H |
|---|---|---|---|---|---|---|---|---|---|---|
| Healthy | 32.20 | 38.89 | 88.37 | 67.58 | 81.93 | 90.58 | 92.86 | 91.57 | 68.66 | 101.71 |
| Overweight | 42.62 | 56.73 | 156.03 | 81.02 | 96.62 | 108.97 | 120.09 | 113.53 | 74.77 | 188.57 |
| Obese | 55.36 | 72.13 | 189.00 | 102.22 | 134.13 | 163.29 | 178.75 | 167.18 | 84.07 | 204.38 |

Foot regions

**Figure 4.5.** Bar chart for healthy weight, overweight and obese, representing the variation in the ten foot regions

## 4.2 Discussion

The experiment was designed to examine the effect of differences in body mass in adults aged between 25 and 46 years in the three groups (overweight, obese and healthy weight), on plantar pressure distribution characteristics by calculating clinical foot measurements (F, CA, CP, PP and PTI) in ten different foot regions during gait. The findings identified that those who were overweight displayed marked differences in foot loading when compared with adults of healthy weight. Overweight adults generated significantly greater F and CA MF and second to fifth MH regions of the foot, a trend that was similar for the obese adults. Overweight adults also generated an increased CP and PTI under the MF and 2 to 5MHs. A similar trend was found for the obese adults with significant differences also found at the H in comparison with normal weight adults.

Plantar foot pressure parameters such as PP and CP presented statistically remarkable rises with increasing weight. This was noticed with the rising volunteer BMI class. The results provide important objective information regarding the functional limitations specific to foot mechanics in dynamic (walking) situations.

Observing the marked dissimilarity in plantar pressures as a function of increased adiposity (BMI), it is interesting to speculate on the structural consequences of repetitive loading on the feet and other parts of the lower extremity.

The physiological manifestations of loading may be reflected in self-reported pain, soreness or discomfort in the lower extremity as a consequence of the increased pressures and forces acting on the musculoskeletal structure of the human foot. For instance, plantar heel pain is commonly characterised by pain and tenderness on the calcaneal tuberosity at the point of attachment of the plantar fascia (Hill & Cutting, 1989). Although the specific aetiology of plantar heel pain is unknown, a number of studies (Cousins et al., 2013; Dowling et al., 2001; Dowling et al., 2004; Mickle et al., 2006; Yan et al., 2013; Hill & Cutting, 1989) have reported that increased body weight is an associated factor.

There is a suggestion that musculoskeletal pain in the lower extremity may cause people to alter their gait pattern in an attempt to avoid or minimise discomfort (Messier et al., 1995). Additionally, McGoey et al. (1990) stated that chronic musculoskeletal pain is common in morbidly obese individuals and that weight loss can lead to significant relief in self-reported pain. Other researchers have reported a decreased sensitivity in the feet of diabetics, skin breakdown and a predisposition to foot ulceration associated with neuropathy in individuals with higher static pressures under the feet (Vela et al., 1998; Cavanagh et al., 1985). Ease of walking, as determined via discomfort experienced in the feet, may be a major limiting factor in the predisposition of the obese (including diabetics who are overweight and obese) to participate in habitual physical activity such as walking. Nyska et al. (1997) pointed out that the foot adapts itself to excessive weight bearing by maintaining the medial longitudinal arc. Excessive weight bearing due to increased body weight in subjects with obesity is believed to cause structural foot dysfunction, such as the collapse of the longitudinal arc, which especially leads to an increased middle foot contact area (Riddiford-Harland et al., 2000).

### 4.2.1. Force and contact area

The F values of the whole foot were the higher mean value in obese and overweight adults, while the lowest F mean value with healthy weight adults. Changes in PF data was largely detected owing to body mass. However, the findings at the H and forefoot (specifically 2MH, 3MH and $1^{st}$T) for adults who are obese and overweight, demonstrated increased loading at these sites. These results are consistent with previous research (Dowling et al., 2001; Yan et al., 2013). These findings have identified elevated levels of loading, in children who are obese at the plantar H, MF and 2MH to 5MH when compared with non-obese children.

The outcomes for F, found by Mickle et al. (2006), correspond with those of this study. They found that H, MF and forefoot had the higher F value. The objective of the study undertaken by Mickle et al. (2006) was to determine the effects of overweight and obesity on plantar pressures generated by pre-school children during gait. They emphasised that higher stress made the feet of overweight/obese children vulnerable to bone fatigue and soft tissue damage due to higher F over larger CA.

A noteworthy main effect of obesity on dynamic CA was also found as shown in **(Figure 4.2)**. The higher foot CA in overweight and obese adults was compared with their normal-weight counterparts. The higher CA was measured in both groups under the H, MF, 1MH, 2MH, and 3MH anatomical regions. In this study, the higher CA within MF was confirmed by previous research (e.g., Hills et al., 2001; Prabhu et al., 2001; Periyasamy et al., 2012). These studies stressed that the foot pressure distribution parameter power ratio value is greater for diabetic foot than the normal foot (Prabhu et al., 2001). This power ratio value decreases as the BMI increases because the total contact area increases due to exposure to higher loads and does not depend on larger feet. Hence this study found significant variations in power ratio value in MF and the plantar ground contact area of overweight subjects compared with healthy subjects while standing, because plantar pressure increase begins from the MF in low grade obese subjects (i.e. overweight) due to an increase CA in MF.

Mickle et al. (2006) outcomes for CA correspond with those of this study. They found H, MF and forefoot CA were higher in overweight and obese compare to healthy children. The objective of this study undertaken by Mickle et al., (2006), determines the effects of overweight and obesity on plantar pressures generated by pre-school children through walk. They underlined that increased CA was not found to be sufficient to compensate for the high F generated during walking, thus causing higher plantar pressure with increased stress (Mickle et al., 2006).

Considering that the obese group had the greatest CA and that the greatest difference between the groups obese and non-obese in terms of the current results disagree with those of Filippin et al., (2007). The objective of the research undertaken by Filippin et al., (2007) was to determine if there were differences in static and dynamic plantar pressure distribution between obese and eutrophic children and specifically, where the pressure is located on the foot and in what proportion it correlates to body mass. It is acceptable to assume that the obese children displayed flattening of the medial longitudinal arch. In contrast, it is not yet clear why this flattening and consequently, the rise in CA in the MF region, occurs.

#### 4.2.2. Contact pressure and pressure-time integrals

As described in the results section, overweight and obese adults have a higher value of CP at the H, 2MH, 3MH, 1MH, 1$^{st}$T and MF regions. These increased the CP consequences are compatible with Hills et al. (2001). Hills et al. (2001) investigated plantar pressure differences between obese and non-obese adults during standing and walking protocols using a pressure distribution platform. They highlighted the cause for subjects to have a higher body weight.

In this study, the CP was statistically significantly higher in the H, 2MH, 3MH, 1MH, 1$^{st}$T and MF regions. This finding was dissimilar to the finding of Yoon et al. (2016), who found that no notable change was observed in the PP in forefoot and H areas. Yoon et al. (2016) determined foot stability according to the results of plantar pressure and spontaneity balance in the normal group and in the obesity, group based on BMI, using a pressure distribution platform. They accentuated the cause for participants to a reduction in the spontaneity balance index in the H region of both the healthy and obese BMI categories. This is thought to be a mechanism of compensating for the decreased hindfoot balance in the forefoot area, with forefoot pressure increasing to compensate for balance.

PTI also referred to as impulse, was found to be statistically higher beneath the H, 1$^{st}$T, 2$^{nd}$T, 3MH, 1MH and MF. PTI measured value, gives details regarding weight distribution through time. The PTI outcomes for Mickle et al. (2006) correspond with those of this study. Mickle et al. (2006) found that the MF displayed significantly higher values. The objective of the study undertaken by Mickle et al. (2006), determine the effects of overweight and obesity on plantar pressures generated by pre-school children during gait. They confirm that the higher stress and, in turn, vulnerability to bone fatigue and soft tissue damage to higher forces over larger contact areas, occurs in the overweight/obese children

In this study, the PTI was statistically significantly higher in 1MH to 3MH. This finding is similar to the finding of Putti et al. (2010). Putti et al. (2010) investigated the in-shoe pressure differences in Caucasians and Indians. This variable is thought to be important in the pathogenesis of skin lesions (Fuller, 1996).

### 4.2.3. Peak pressure

As for peak pressure (PP), the obese adults generally displayed greater values than the healthy group during gait, however, the H, 1$^{st}$T and metatarsal head regions in particular (2MH, 3MH and 1MH) suffered greater pressure, and the 3$^{rd}$-5$^{th}$T area had the lowest peak pressure, as presented in **(Figure 4.5)**. The results are in accordance with (Hills et al., 2001; Dowling et al., 2001; Filippin et al., 2007). The objective of the study by Filippin et al. (2007) was to determine if there are differences in static and dynamic plantar pressure distribution between obese and eutrophic children and, specifically, where the pressure is located on the foot and in what proportion it correlates to body mass. Butterworth et al. (2015) also found weight to be a significant independent predictor of PP under the H, MF and forefoot. The purpose of the study by Vela et al., (1998) was to determine if increased weight contributes to increased mean PP foot pressures when foot function, deformity and structure are controlled.

The PP outcomes from Mickle et al. (2006) correspond with those of this study. Mickle et al. (2006) found that the MF displayed a significantly higher value. The objective of this study undertaken by Mickle et al., (2006) determines the effects of overweight and obesity on plantar pressures generated by pre-school children during gait. They confirm that the higher stress and, in turn, vulnerable to bone fatigue and soft tissue damage due to higher F over larger CA, the overweight/obese children.

In the present study, it was established that the PP mean values were statistically notably higher under the H, 1$^{st}$T and metatarsal head regions in particular (2MH, 3MH and 1MH). These findings were in absolute agreement with those of Yan et al. (2013), who found that no significant change was observed in the forefoot and hind-foot PP. Yan et al. (2013) study was designed to examine the effects of obesity on dynamic plantar pressure distribution during walking for prepubescent children, using a plantar pressure plate system. They emphasised that higher plantar pressure in obese children will increase loading on the developing foot and may result in foot discomfort and possibly deformity, which may increase the risk of injury.

In this study, the highest PP was found under the H region. These findings are supported by studies investigating foot function in children (Bosch et al., 2007; Müller et al., 2012; Phethean et al., 2014; Bosch et al., 2009) and adults (Putti et al., 2008; Bosch et al., 2009; Scott et al., 2007).

## 4.3 Chapter summary

The present study has demonstrated differences between plantar foot loading characteristics of obese, overweight and healthy weight adults, aged 25–46 years, during level walking. Obese and overweight adults showed increases in heel and forefoot foot regions. The highest foot pressure measure increases in the obese were found under the heel of the foot and the metatarsal heads. Compared with the non-obese groups, there were increases in pressure under the H, MF and the middle of the forefoot (2MH and 3MH). This difference is the result of reduced strength of the ligaments of the foot in obese individuals. These findings have implications for pain and discomfort in the lower extremity in the obese, the choice of footwear and predisposition to participate in activities of daily living such as walking. Further study in this area is warranted.

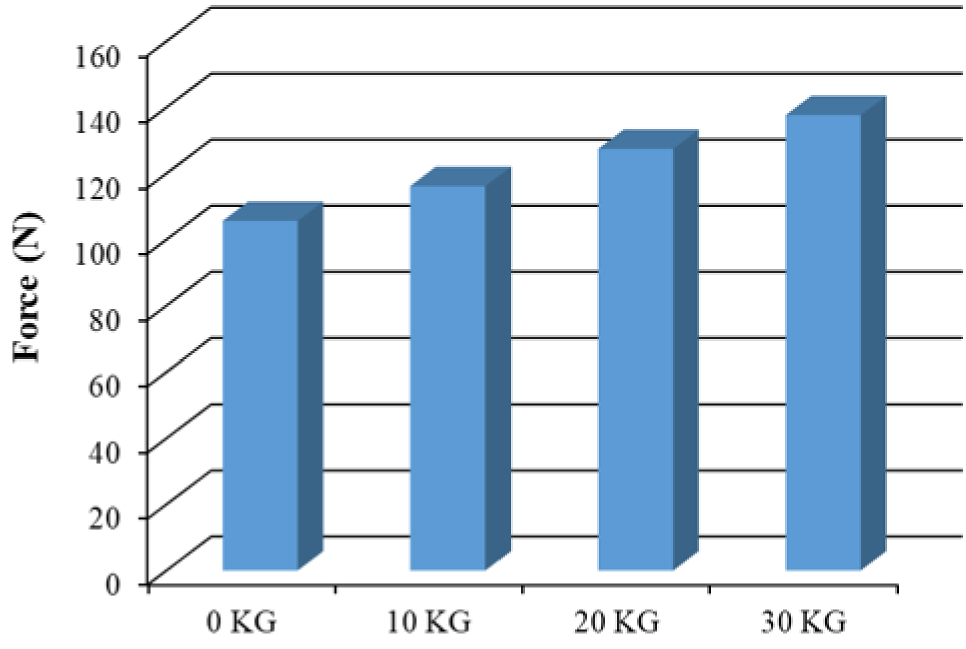
The next chapter aims to answer objective two, which involves simulation body weight to determine plantar pressure data variables during the loading phase of the gait.

# 5. RESULT OF EXPERIMENT 2

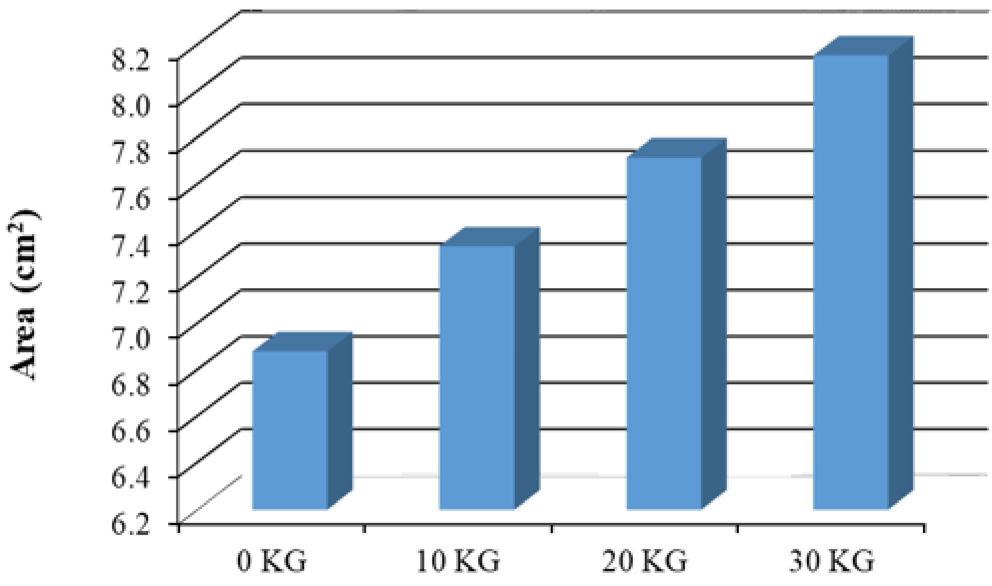
## 5.1. Introduction

This chapter focuses on covering the main results of the simulated bodyweight experiment. The first section of the chapter considers experiment two’s objective, which was to estimate the effect of simulated body mass on foot plantar measurers force (F), contact area (CA), contact pressure (CP), pressure time integral (PTI), and peak pressure (PP). The second section of the chapter measures the repeatability F-Scan system for the result through foot plantar measures (F, CA, CP, PTI, and PP). The chapter discussion is presented in the next section and the last section focuses on the chapter summary.

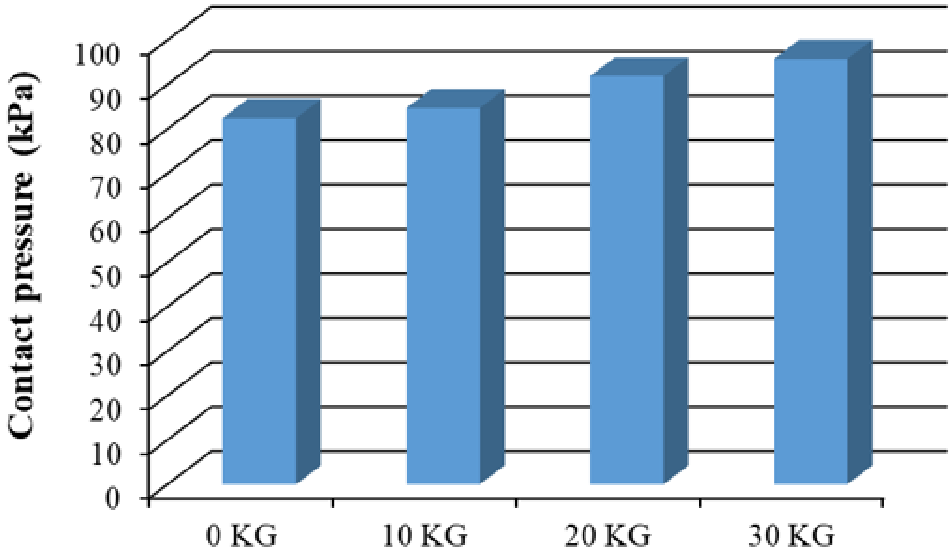
The experiment was conducted to investigate the influence of simulated body weight on the plantar pressure parameters during gait. Both feet (62 feet) in a total of thirty-one participants were examined. The characteristics of the participants were as (mean ±SD) follows: age 37.55±6.92 years, body weight 89.82±17.92 kg, height 1.74±0.08 cm, and BMI 46.00±20.1 kg/m$^2$, respectively. Statistically significant correlation coefficients ($P < 0.001$) have been found between simulated body weight (SBW) (an increase in load) with the main effects on all foot variables (F, CA, CP, PTI and PP). Parameters were statistically observed to increase their values gradually under SBW, which may present problems for the longer-term compared with the normal group (NBW, 0 kg). This effect was consistent at any given simulated body weight as displayed in **(Figure 5.1 A, B, C, D, E).**



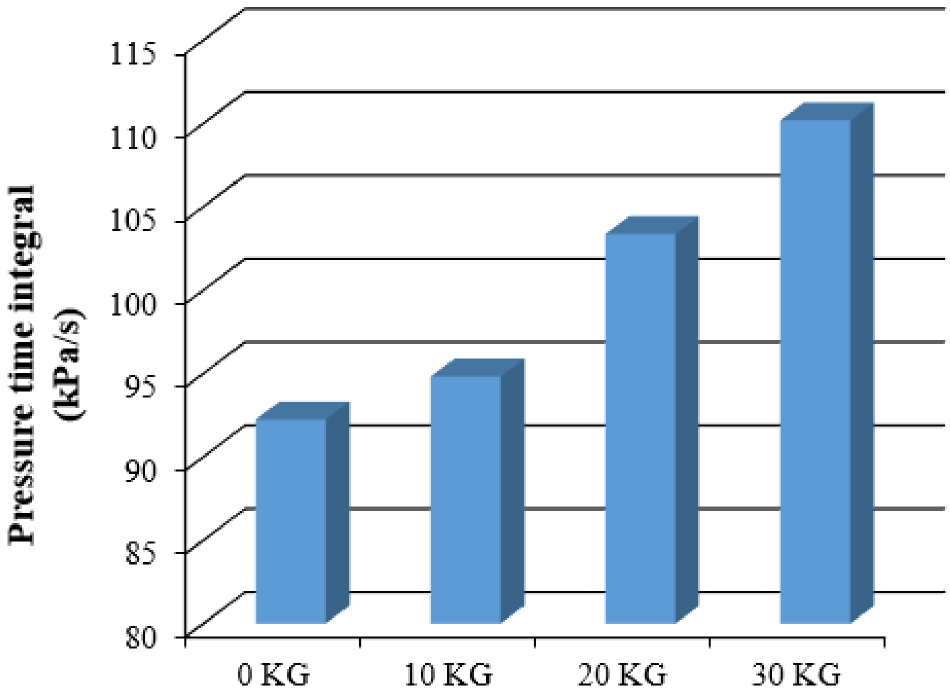

**(A) Simulated body weight**




**(B) Simulated body weight**




(C) Simulated body weight




(D) Simulated body weight

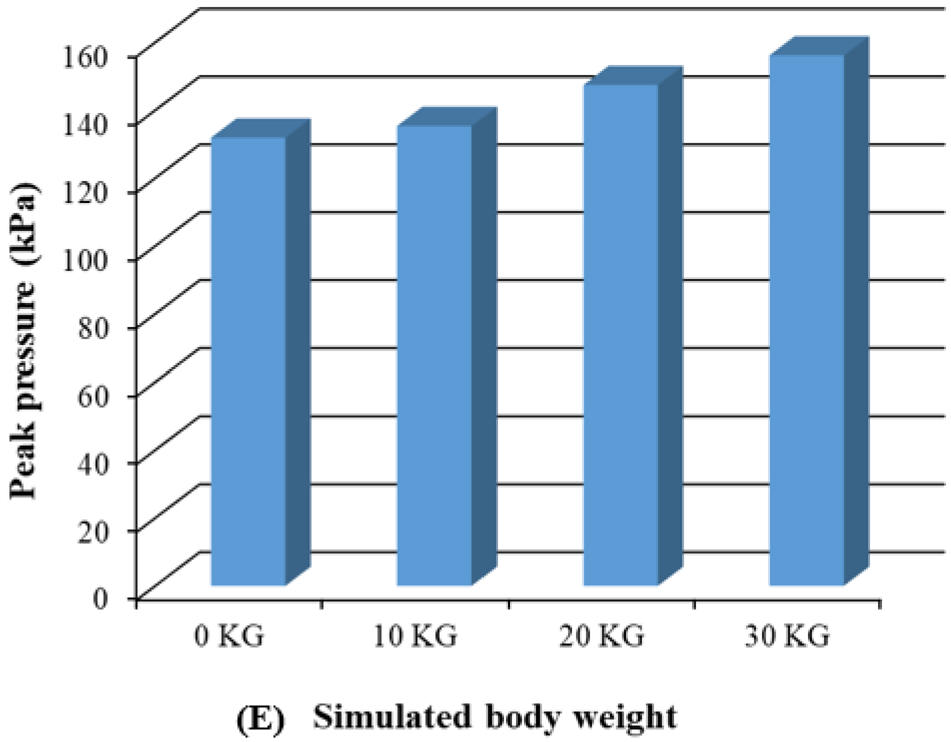



**Figure 5.1.** The average effect of simulated body weight on foot plantar pressure (**A-** force, **B-** contact area, **C-** contact pressure, **D-** pressure time integral, and **E-** peak pressure)

### 5.1.1. Force

Force (F) measure was studied with SBW and resulted in a notable rise in mean F variables between 30, 20, and 10 kg load simulations compared to the NBW (0 kg) group in all foot regions. The F measure values with increased body weight are presented in **Table 5.1**. The F variable displayed a mean increase under the H, 1MH, 2MH, 3MH and MF regions, showing significant agreements ($P < 0.001$) with SBW.

In the 30, 20, 10, and 0 kg simulations, mean F value was significantly greater in the H value with 370.81, 354.89, 321.53 and 307.42 N, followed by 1MH zone with 142.69, 133.35, 117.44 and 105.74 N; 2MH region with 113.68, 104.39, 95.52 and 80.56 N, in the MF region with mean F values at 78.69, 66.75, 60.44 and 51.45N, respectively.

In the 30 kg SBW load, F was significantly larger in all regions of the foot compared with other load conditions, but there was a small change in all SBWs (10, 20, 30 kg) under the $3^{rd}$-$5^{th}$T with mean value 17.51, 17.30 and 17.08 N, $2^{nd}$T with mean value 12.75, 10.36 and 9.98 N, and $1^{st}$T with mean value 66.96, 66.81 and 62.28 N regions, compared with NBW group (0 kg) which had a mean value of 15.46, 9.97 and 58.38 N.

Individual means of all the three repeated trials for each foot were calculated, and these values were used to calculate the between-weights coefficient of variance (CV) for all parameters, since this was shown to be accepted methods of measuring reliability between testing sessions. Measurements with a higher CV were recorded mainly under the toes. CV values for the regional F pressures ranged between SBW and NBW (0 kg), as shown in **Table 5.1.**

**Table 5.1.** Force measure with increased body weight for ten regions of the foot

| Foot region | Force (N) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV |
| **3rd-5thT** | 15.46 | 5.83 | 1.29 | 17.08 | 7.85 | 1.12 | 17.30 | 7.30 | 0.92 | 17.51 | 7.39 | 1.03 |
| **2ndT** | 9.97 | 3.53 | 1.18 | 9.98 | 3.96 | 0.86 | 10.36 | 4.71 | 0.90 | 12.75 | 5.67 | 0.97 |
| **1stT** | 58.38 | 12.45 | 0.79 | 62.28 | 11.20 | 1.03 | 66.81 | 18.33 | 0.79 | 66.96 | 18.14 | 0.80 |
| **5MH** | 35.13 | 18.36 | 0.59 | 39.62 | 19.02 | 0.73 | 42.37 | 23.61 | 0.52 | 46.11 | 24.78 | 0.45 |
| **4MH** | 55.30 | 20.57 | 0.47 | 62.55 | 19.99 | 0.50 | 70.64 | 20.28 | 0.36 | 75.59 | 29.83 | 0.33 |
| **3MH** | 71.78 | 34.37 | 0.41 | 83.07 | 43.53 | 0.43 | 93.19 | 36.92 | 0.34 | 101.77 | 37.92 | 0.31 |
| **2MH** | 80.56 | 39.32 | 0.43 | 95.52 | 42.36 | 0.37 | 104.39 | 44.25 | 0.37 | 113.68 | 44.58 | 0.33 |
| **1MH** | 105.74 | 56.21 | 0.97 | 117.44 | 56.37 | 0.41 | 133.35 | 68.03 | 0.45 | 142.69 | 70.01 | 0.41 |
| **MF** | 51.45 | 26.57 | 0.84 | 60.44 | 28.25 | 0.87 | 66.75 | 36.23 | 0.78 | 78.69 | 39.14 | 0.71 |
| **H** | 307.42 | 133.63 | 0.38 | 321.53 | 134.80 | 0.40 | 354.89 | 142.87 | 0.35 | 370.81 | 140.40 | 0.33 |

### 5.1.2. Contact area

The CA measure was also investigated with SBW. There was a significant difference in ($P < 0.001$) in CA between SBW and NBW (0 kg), as shown in **Table 5.2.** The three main regions that made the largest CA were the insole system starting with the H region with 19.11, 18.19, 17.29 and 16.26 $cm^2$, followed by 1MH with 8.97, 8.15, 7.74, 6.02 $cm^2$, and the MF with measurements of 8.87, 7.96, 6.28, 4.82 $cm^2$.

However, in the simulated body weights (30, 20 and 10 kg), the CA demonstrated a slight increase within the $2^{nd}$T with a mean value were 0.99, 0.81, and 0.70 $cm^2$, compared to the unweighted control group which had a CA value of 0.67 $cm^2$ in the same region. The CA value located at the $3^{rd}$-$5^{th}$T in SBW (30, 20, and 10 kg) were modest changes compared to the NBW control group. The values under the $3^{rd}$-$5^{th}$T area were 1.57, 1.55, 1.46 $cm^2$ while the CA value in the NBW group was 1.42 $cm^2$.

**Table 5.2.** Contact area measure with increased body weight for ten regions of the foot

| Foot region | Area ($cm^2$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV |
| **3rd-5thT** | 1.42 | 2.69 | 1.29 | 1.46 | 1.03 | 0.61 | 1.55 | 1.06 | 0.66 | 1.57 | 1.24 | 0.71 |
| **2ndT** | 0.67 | 0.6 | 1.18 | 0.70 | 1.35 | 1.12 | 0.81 | 0.51 | 0.60 | 0.99 | 0.55 | 0.62 |
| **1stT** | 3.11 | 1.73 | 0.79 | 3.30 | 2.1 | 0.49 | 3.54 | 1.54 | 0.43 | 3.86 | 1.59 | 0.39 |
| **5MH** | 3.00 | 1.73 | 0.59 | 3.16 | 1.66 | 0.45 | 3.44 | 1.76 | 0.46 | 4.96 | 1.96 | 0.44 |
| **4MH** | 3.98 | 1.72 | 0.47 | 4.24 | 1.64 | 0.32 | 4.58 | 1.58 | 0.30 | 4.79 | 1.45 | 0.25 |
| **3MH** | 4.42 | 1.53 | 0.41 | 4.86 | 1.56 | 0.28 | 5.18 | 1.45 | 0.24 | 5.40 | 1.33 | 0.22 |
| **2MH** | 4.60 | 1.62 | 0.43 | 5.20 | 1.51 | 0.26 | 5.26 | 1.48 | 0.25 | 5.88 | 1.54 | 0.24 |
| **1MH** | 6.02 | 3.18 | 0.97 | 7.74 | 2.98 | 0.35 | 8.15 | 3.61 | 0.36 | 8.97 | 3.29 | 0.34 |
| **MF** | 4.82 | 5.75 | 0.84 | 6.28 | 5.77 | 0.88 | 7.96 | 5.99 | 0.81 | 8.87 | 5.63 | 0.69 |
| **H** | 16.26 | 6.8 | 0.38 | 17.29 | 5.69 | 0.29 | 18.19 | 5.7 | 0.28 | 19.11 | 7.15 | 0.31 |

### 5.1.3. Contact pressure

The highest contact pressure (CP) was found under the 2MH, H, and 3MH regions with SBW states, which are displayed in **Table 5.3**. The difference between the averages of the four states was significant ($P < 0.001$). The mean CP values under 30, 20 and 10 kg weight were beneath the 2MH with 149.11, 135.55 and 116.99 kPa, while the NBW (0 kg) had the mean value for same the zone with 110.48 kPa. In addition, the H area was presented as statistically significant in all SBW loads and was greatest with 30 kg followed by 20, and 10 kg weight compared with the NSBW (0 kg). The values for both loads were 146.24, 139.10, 122.07 kPa and 111.15 kPa. Furthermore, the CP value with SBW at 30, 20 and 10 kg compared with NBW group (0 kg) within 3MH region showed 130.22, 122.70, 111.86 kPa and 103.85 kPa.

However, in relation to the smaller changes in CP value with the increased SBW in mean contact pressure under the $3^{rd}$–$5^{th}$T region, the values for this region with all control and SBW were 32.13, 40.23, 43.35, 49.70 kPa, respectively. The CP value was approximately double that under the MF within 30, 20 and 10 kg loads with a mean value 89.16, 60.78, 55.48 kPa compared with the NBW group, which had a mean value of 43.25 kPa.

**Table 5.3.** Contact pressure measure with increased body weight for ten regions of the foot

| Contact pressure (kPa) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | **Zero kg** | | | **10 kg** | | | **20 kg** | | | **30 kg** | | |
| | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV |
| **3rd-5th T** | 32.13 | 60.4 | 0.89 | 40.23 | 29.74 | 0.50 | 43.35 | 30.79 | 0.57 | 49.70 | 28.51 | 0.57 |
| **2nd T** | 37.87 | 38.61 | 0.72 | 39.96 | 31.71 | 0.68 | 41.53 | 29.8 | 0.69 | 46.05 | 39.42 | 0.78 |
| **1st T** | 78.54 | 72.29 | 0.73 | 80.97 | 61.47 | 0.60 | 82.97 | 58.88 | 0.64 | 88.02 | 60.87 | 0.65 |
| **5MH** | 54.78 | 32.12 | 0.42 | 69.30 | 30.29 | 0.37 | 74.01 | 29.92 | 0.33 | 81.46 | 37.79 | 0.37 |
| **4MH** | 89.58 | 37.14 | 0.35 | 94.96 | 31.8 | 0.29 | 103.64 | 31.96 | 0.26 | 110.51 | 34.71 | 0.27 |
| **3MH** | 103.85 | 44.3 | 0.35 | 111.86 | 38.55 | 0.30 | 122.70 | 40.46 | 0.28 | 130.22 | 39.02 | 0.26 |
| **2MH** | 110.48 | 55.87 | 0.39 | 116.99 | 41.53 | 0.32 | 135.55 | 90.38 | 0.53 | 149.11 | 58.27 | 0.34 |
| **1MH** | 73.42 | 35.87 | 0.37 | 88.09 | 32.79 | 0.33 | 101.23 | 83.89 | 0.60 | 111.96 | 35.03 | 0.30 |
| **MF** | 43.25 | 36.17 | 0.51 | 55.48 | 32.22 | 0.47 | 60.78 | 44.9 | 0.51 | 89.16 | 46.21 | 0.45 |
| **H** | 111.15 | 78.14 | 0.71 | 122.07 | 68.92 | 0.40 | 139.10 | 83.01 | 0.44 | 146.24 | 64.95 | 0.37 |

### 5.1.4. Pressure time integral measurement

The pressure time integral (PTI, kPa/s) measure was also investigated with SBW. There was a significant difference in ($P < 0.001$) in PTI between SBW and NBW groups. There were notably increases between the 30 kg, 20 kg and 10 kg load compared with the NBW group (0 kg) status within the H, 2MH, 3MH, 4MH, 1MH, 1$^{st}$ T, 5MH and MF which are shown in **Table 5.4.**

The three main regions that made the largest PTI were the insole system starting with the H region with 169.58, 151.92, 140.71 and 120.84 kPa/s; 2MH region with 154.04, 142.94, 126.41 and 119.79 kPa/s; and 3MH area with 146.15, 133.78, 123.37 and 118.18 kPa/s; 4MH region with 124.44, 114.1, 103.35 and 92.46 kPa/s, followed by the 1MH region 121.71, 108.17, 96.31 and 83.25 kPa/s; and the 1$^{st}$T region with 116.8, 97.01, 96.05 and 84.43 kPa/s, respectively.

However, in the SBW (30, 20 and 10 kg), the PTI demonstrated a slight increase within the 2$^{nd}$T with a mean value were 62.26, 51.58, and 48.66 kPa/s, compared to the NBW control group which had a PTI value of 41.94 kPa/s in the same region. The PTI value located at the 3$^{rd}$-5$^{th}$T in simulated body weight groups (30, 20, and 10 kg) was modest changes than the unweighted control group. And the value under the 3$^{rd}$-5$^{th}$T area were 73.3, 61.52 and 59.46 kPa/s while the PTI value in NBW group was 43.68 kPa/s.

**Table 5.4.** Pressure time integral measure with increased body weight for ten regions of the foot

| Pressure time integral (kPa/s) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | **Zero kg** | | | **10 kg** | | | **20 kg** | | | **30 kg** | | |
| | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV | Mean | SD | %CV |
| **3rd-5thT** | 43.68 | 99.61 | 1.24 | 59.46 | 45.63 | 0.71 | 61.52 | 48.26 | 0.79 | 73.3 | 60.6 | 0.89 |
| **2ndT** | 41.94 | 76.3 | 1.07 | 48.66 | 47.54 | 0.86 | 51.58 | 46.76 | 0.89 | 62.26 | 52.36 | 0.88 |
| **1stT** | 84.43 | 140.61 | 1.08 | 96.05 | 83.26 | 0.73 | 97.01 | 83.86 | 0.79 | 116.8 | 86.18 | 0.78 |
| **5MH** | 69.28 | 45.05 | 0.53 | 75.61 | 31.13 | 0.34 | 87.18 | 160.72 | 1.23 | 99.38 | 44.16 | 0.40 |
| **4MH** | 92.46 | 59.52 | 0.52 | 103.35 | 37.62 | 0.32 | 114.1 | 41.09 | 0.30 | 124.44 | 49.13 | 0.35 |
| **3MH** | 118.18 | 65.91 | 0.50 | 123.37 | 54.24 | 0.36 | 133.78 | 45.92 | 0.30 | 146.15 | 54.45 | 0.34 |
| **2MH** | 119.79 | 65.75 | 0.47 | 126.41 | 45.67 | 0.33 | 142.94 | 53.98 | 0.35 | 154.04 | 61.62 | 0.38 |
| **1MH** | 83.25 | 51.18 | 0.46 | 96.31 | 39.7 | 0.38 | 108.17 | 48.88 | 0.41 | 121.71 | 42.59 | 0.35 |
| **MF** | 50.06 | 40.51 | 0.56 | 67.43 | 36.58 | 0.47 | 71.39 | 41.02 | 0.48 | 89.28 | 64.69 | 0.59 |
| **H** | 120.84 | 148.94 | 0.78 | 140.71 | 103.59 | 0.58 | 151.92 | 115.01 | 0.58 | 169.58 | 116.37 | 0.63 |

### 5.1.5. Peak pressure

Observed values for the PP depicted maximum values in this test, with SBW; 30, 20 and 10 kg groups compared with NBW group beneath fifth regions of the ten regions. These regions were the H, 2MH, 3MH, 1MH and $1^{st}$ T. Furthermore, the main values for these regions were (256.49, 207.68, 192.68, 188.35 and 167.49 kPa); (242.44, 195.42, 180.18, 167.36 and 152.66 kPa); followed by (227.14, 173.09, 160.60, 148.95 and 145.07 kPa), and (211.57, 147.26, 142.28, 136.52 and 132.96 kPa), respectively. The PP showed a fluctuating higher value in specific simulations compared with control simulations within the $3^{rd}$-$5^{th}$T and $2^{nd}$T, which were 7.29, 9.39, 42.64 and 36.91 kPa and 63.44, 54.83, 53.08 and 31.91 kPa, respectively. There were statistically significant increases between the 20 and 30 kg weights and NBW group (0 kg) within the H, 2MH, 3MH, 1MH, $1^{st}$T, and 4MH as displayed in **(Figure 5.2).**

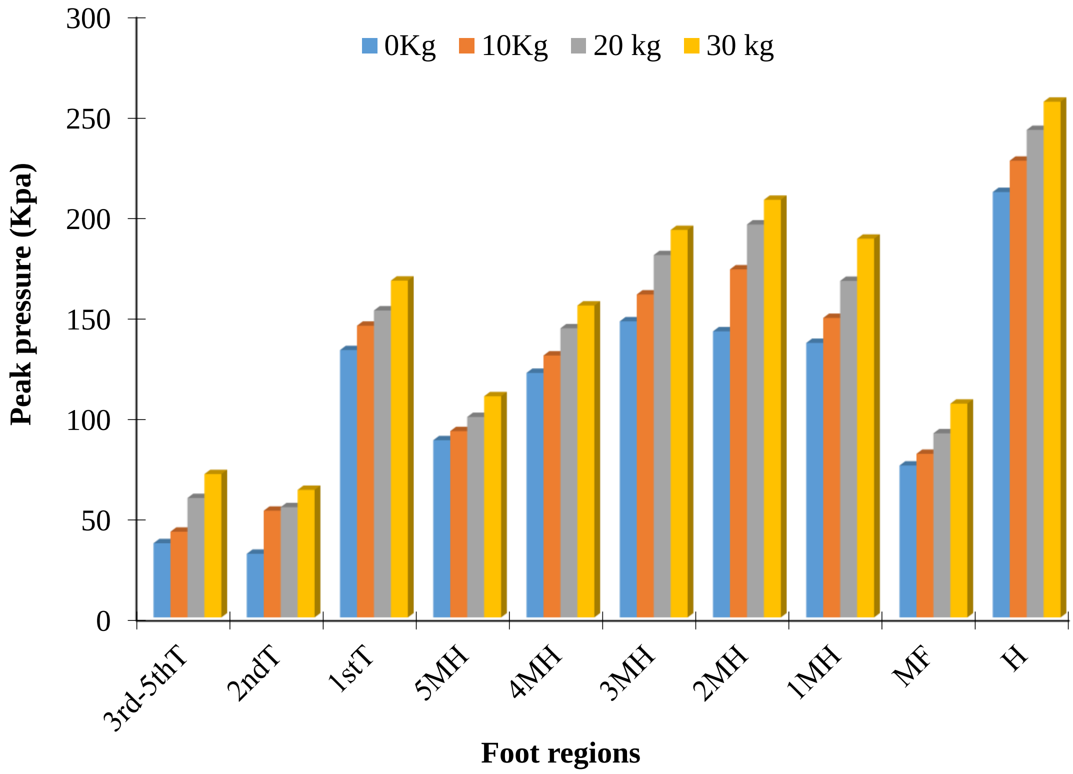



**Figure 5.2.** Comparison of peak pressure parameter among simulated body weight under four weighted simulations for ten regions of the foot. The next section focuses on the coefficients of repeatability for the insole system

## 5.2. Repeatability of the F-Scan system

The results of the ICC for analysis shows a generally good level of reliability, the quality of which is dependent on the region of the foot and the variable investigated with SBW loads. This research displayed that high between-day reliability could be obtained between testing days in healthy, symptom-free participants, using SPSS software to calculate ICC values by applying model two. Lower reliability was found in the typically less-loaded areas, such as the $3^{rd}$-$5^{th}$T. For this dissertation, Model 2 is used to calculate the reliability of gait variables since it is a repeated measures method. In addition, the sample size requirements are computed based on the ICC values. Detailed calculating via a two-way mixed effects model has been applied and is highlighted in **chapter 3, section 3.5.3**.

It must be realised however, that the results apply only for the specific instrument that was used here and is not generally transferable to other available pressure distribution measurement systems. These may be established on various sensor technologies and may not achieve comparable reliability. In addition, the F-Scan masking method may limit our ability to generalise the conclusions from this study to a wider population. The F-Scan mask method, selected for its strong reputation as a valid method of dividing the foot into anatomical regions of interest, still makes assumptions regarding the boundaries of particular regions. In addition, areas such as the MF may become under-represented by such masking algorithms therefore, when investigating afflictions such as Pes planovalgus, an investigator may choose a mask which is more appropriate for this examination. However, since the examination being attempted in this study was of a non-specific nature, the more generic mask was selected.

The study showed that all measures are repeatable. From the outcome data highlighted in this study (F, CA, CP, PTI and PP), it can be seen that the findings support the application of an in-shoe pressure capturing system as a dependable clinical investigation modality. These applications include evaluating the pressure distribution under the feet in various common foot pathologies, diabetic foot disorders, pre-operative assessment of foot deformity, objectively assessing the success of corrective foot surgery and assessment of rheumatoid arthritis.

### 5.2.1. Force variable

Positive outcomes were attained at the baseline, as shown in **Table 5.5**. All anatomical regions of the foot was researched. It allowed the potential to notice 'good to excellent' ICC values for the three-positions: left, right and both feet. ICC values for both feet column is obtained by calculating the average left foot and right foot as presented in **Table 5.5.** As indicated in the calculation, the reliability ICC value ranges between (0.75 - 0.98) foot area locations, respectively which scored 'good and excellent' ICC values. Therefore, the results display an acceptable repeatability trend when the F variable was measured at the baseline with un-weighted and additional weights. Detailed calculating two-way mixed effects model which has been applied, is shown in **chapter 3, section 3.5.3**.

**Table 5.5.** Intra-class correlation coefficients result for F-Scan system regarding force variable

| Force (N) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Left | Right | Both | Left | Right | Both | Left | Right | Both | Left | Right | Both |
| **3rd-5thT** | 0.97 | 0.80 | 0.89 | 0.92 | 0.89 | 0.90 | 0.86 | 0.82 | 0.84 | 0.93 | 0.96 | 0.94 |
| **2ndT** | 0.93 | 0.76 | 0.85 | 0.93 | 0.77 | 0.85 | 0.88 | 0.86 | 0.87 | 0.93 | 0.93 | 0.93 |
| **1stT** | 0.90 | 0.86 | 0.88 | 0.88 | 0.75 | 0.82 | 0.94 | 0.96 | 0.95 | 0.98 | 0.97 | 0.98 |
| **5MH** | 0.78 | 0.88 | 0.83 | 0.81 | 0.77 | 0.79 | 0.84 | 0.94 | 0.89 | 0.87 | 0.87 | 0.87 |
| **4MH** | 0.80 | 0.87 | 0.84 | 0.91 | 0.76 | 0.84 | 0.85 | 0.93 | 0.89 | 0.89 | 0.84 | 0.87 |
| **3MH** | 0.91 | 0.93 | 0.92 | 0.93 | 0.76 | 0.85 | 0.86 | 0.92 | 0.89 | 0.76 | 0.90 | 0.83 |
| **2MH** | 0.95 | 0.96 | 0.95 | 0.94 | 0.78 | 0.86 | 0.82 | 0.94 | 0.88 | 0.94 | 0.95 | 0.95 |
| **1MH** | 0.86 | 0.91 | 0.88 | 0.88 | 0.92 | 0.90 | 0.80 | 0.92 | 0.86 | 0.92 | 0.91 | 0.91 |
| **MF** | 0.89 | 0.89 | 0.89 | 0.92 | 0.84 | 0.88 | 0.96 | 0.94 | 0.95 | 0.95 | 0.94 | 0.94 |
| **H** | 0.96 | 0.92 | 0.94 | 0.89 | 0.90 | 0.89 | 0.93 | 0.96 | 0.93 | 0.92 | 0.95 | 0.93 |

### 5.2.2. Contact area variable

As shown below in **Table 5.6**, the data analysis of the contact area (CA) measure, obtained positive results at the baseline. In all ten anatomical zones considered, it was observed to have 'good and excellent' ICC values for the states: left, right and both feet. ICC value ranges between (0.78 - 0.99) foot region locations, respectively which scored 'good and excellent' ICC values. Detailed calculating two-way mixed effects model which has been applied, is shown in **chapter 3, section 3.5.3**.

**Table 5.6.** Intra-class correlation coefficients result for F-Scan system regarding contact area at baseline

| Area ($cm^2$) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Left | Right | Both | Left | Right | Both | Left | Right | Both | Left | Right | Both |
| **3rd-5th T** | 0.82 | 0.85 | 0.84 | 0.94 | 0.80 | 0.87 | 0.92 | 0.85 | 0.88 | 0.94 | 0.90 | 0.92 |
| **2nd T** | 0.92 | 0.78 | 0.85 | 0.78 | 0.87 | 0.79 | 0.91 | 0.87 | 0.89 | 0.91 | 0.93 | 0.92 |
| **1st T** | 0.89 | 0.91 | 0.90 | 0.99 | 0.92 | 0.96 | 0.92 | 0.91 | 0.91 | 0.93 | 0.93 | 0.93 |
| **5MH** | 0.93 | 0.94 | 0.94 | 0.93 | 0.97 | 0.95 | 0.93 | 0.95 | 0.94 | 0.83 | 0.94 | 0.89 |
| **4MH** | 0.94 | 0.90 | 0.92 | 0.86 | 0.93 | 0.90 | 0.94 | 0.94 | 0.94 | 0.94 | 0.88 | 0.91 |
| **3MH** | 0.96 | 0.95 | 0.95 | 0.94 | 0.96 | 0.95 | 0.91 | 0.94 | 0.92 | 0.92 | 0.91 | 0.92 |
| **2MH** | 0.95 | 0.95 | 0.95 | 0.94 | 0.92 | 0.93 | 0.93 | 0.94 | 0.93 | 0.93 | 0.94 | 0.94 |
| **1MH** | 0.92 | 0.95 | 0.94 | 0.94 | 0.95 | 0.94 | 0.92 | 0.81 | 0.86 | 0.94 | 0.93 | 0.93 |
| **MF** | 0.97 | 0.95 | 0.96 | 0.98 | 0.97 | 0.97 | 0.99 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 |
| **H** | 0.96 | 0.86 | 0.91 | 0.91 | 0.94 | 0.93 | 0.94 | 0.96 | 0.95 | 0.82 | 0.96 | 0.89 |

### 5.2.3. Contact pressure variable

The CP repeatability results obtained at baseline with the in-shoe pressure system highlighted ‘good to excellent’ ICC results in all of the anatomical areas investigated for the left, right and both feet together, as presented in **Table 5.7.** The ICC value ranges between (0.76 - 0.98) foot region locations.

**Table 5.7.** Intra-class correlation coefficients result for F-Scan system regarding contact pressure at baseline

| Foot region | Contact pressure (kPa) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Left | Right | Both | Left | Right | Both | Left | Right | Both | Left | Right | Both |
| **3rd-5th T** | 0.97 | 0.84 | 0.91 | 0.76 | 0.77 | 0.77 | 0.93 | 0.85 | 0.89 | 0.93 | 0.91 | 0.92 |
| **2nd T** | 0.96 | 0.83 | 0.89 | 0.92 | 0.86 | 0.89 | 0.91 | 0.89 | 0.90 | 0.94 | 0.97 | 0.95 |
| **1st T** | 0.93 | 0.90 | 0.91 | 0.93 | 0.96 | 0.95 | 0.95 | 0.96 | 0.96 | 0.98 | 0.92 | 0.95 |
| **5MH** | 0.85 | 0.91 | 0.88 | 0.90 | 0.93 | 0.91 | 0.79 | 0.94 | 0.86 | 0.85 | 0.92 | 0.89 |
| **4MH** | 0.88 | 0.90 | 0.89 | 0.90 | 0.90 | 0.90 | 0.79 | 0.91 | 0.85 | 0.86 | 0.87 | 0.86 |
| **3MH** | 0.92 | 0.95 | 0.94 | 0.93 | 0.93 | 0.93 | 0.88 | 0.95 | 0.92 | 0.92 | 0.93 | 0.92 |
| **2MH** | 0.94 | 0.77 | 0.86 | 0.92 | 0.91 | 0.91 | 0.85 | 0.95 | 0.90 | 0.77 | 0.95 | 0.86 |
| **1MH** | 0.89 | 0.94 | 0.91 | 0.86 | 0.92 | 0.89 | 0.84 | 0.83 | 0.83 | 0.90 | 0.95 | 0.92 |
| **MF** | 0.89 | 0.98 | 0.93 | 0.97 | 0.86 | 0.92 | 0.93 | 0.78 | 0.86 | 0.88 | 0.96 | 0.92 |
| **H** | 0.87 | 0.94 | 0.91 | 0.94 | 0.94 | 0.94 | 0.81 | 0.96 | 0.88 | 0.91 | 0.92 | 0.92 |

### 5.2.4. Pressure time integral variable

The pressure time integral (PTI) values showed that ‘good to excellent’ ICC scores were found for all anatomical areas at the baseline for the left, right, and both feet, as can be seen in **Table 5.8.** When PTI analysis was carried out, the ICC indicated a highly repeatable trend for most of the anatomical areas investigated, ICC value ranges between (0.77 - 0.97) foot region locations. In all ten anatomical areas investigated, it was possible to observe ‘good’ ICC values for left, right and both feet. The values and results of the ICC for analysis show a generally good level of reliability, the quality of which is dependent on the region of the foot and the variable investigated with SBW loads.

**Table 5.8.** Intra-class correlation coefficients result for F-Scan system regarding pressure time integral at baseline

| | Pressure time integral (kPa/s) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Foot region** | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Left | Right | Both | Left | Right | Both | Left | Right | Both | Left | Right | Both |
| **3rd-5thT** | 0.97 | 0.91 | 0.94 | 0.90 | 0.85 | 0.87 | 0.94 | 0.88 | 0.91 | 0.81 | 0.94 | 0.87 |
| **2ndT** | 0.97 | 0.87 | 0.92 | 0.95 | 0.87 | 0.91 | 0.94 | 0.88 | 0.91 | 0.95 | 0.96 | 0.95 |
| **1stT** | 0.94 | 0.92 | 0.93 | 0.97 | 0.97 | 0.97 | 0.96 | 0.95 | 0.96 | 0.97 | 0.87 | 0.92 |
| **5MH** | 0.95 | 0.87 | 0.91 | 0.80 | 0.83 | 0.82 | 0.85 | 0.91 | 0.88 | 0.85 | 0.91 | 0.88 |
| **4MH** | 0.96 | 0.88 | 0.92 | 0.87 | 0.82 | 0.84 | 0.83 | 0.89 | 0.86 | 0.88 | 0.92 | 0.90 |
| **3MH** | 0.95 | 0.91 | 0.93 | 0.88 | 0.77 | 0.82 | 0.89 | 0.92 | 0.90 | 0.90 | 0.94 | 0.92 |
| **2MH** | 0.91 | 0.90 | 0.91 | 0.92 | 0.89 | 0.90 | 0.94 | 0.90 | 0.92 | 0.81 | 0.95 | 0.88 |
| **1MH** | 0.85 | 0.85 | 0.85 | 0.91 | 0.88 | 0.89 | 0.85 | 0.92 | 0.88 | 0.90 | 0.95 | 0.93 |
| **MF** | 0.89 | 0.89 | 0.89 | 0.93 | 0.83 | 0.88 | 0.89 | 0.87 | 0.88 | 0.87 | 0.96 | 0.91 |
| **H** | 0.89 | 0.96 | 0.92 | 0.93 | 0.94 | 0.93 | 0.89 | 0.95 | 0.92 | 0.96 | 0.91 | 0.94 |

### 5.2.5. Peak pressure

The peak pressure (PP) values displayed that ‘good’ ICC scores were presented for all anatomical areas at baseline for the left, right and both feet, as shown in **Table 5.9.** In all ten anatomical areas for the four simulations tested, there was potential to note ‘excellent’ and ‘good to excellent’ ICC values for left, right and both feet. The ICC value ranges between (0.78 - 0.99) foot region locations. Thus, the findings of this examination display a commonly better level of accuracy, with quality based on the foot region and measures researched.

**Table 5.9.** Intra-class correlation coefficients result for F-Scan regarding peak pressure at baseline

| Foot region | Peak pressure (kPa) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zero kg | | | 10 kg | | | 20 kg | | | 30 kg | | |
| | Left | Right | Both | Left | Right | Both | Left | Right | Both | Left | Right | Both |
| **$3^{rd}$-$5^{th}$T** | 0.97 | 0.86 | 0.92 | 0.85 | 0.78 | 0.82 | 0.87 | 0.85 | 0.86 | 0.92 | 0.91 | 0.92 |
| **$2^{nd}$T** | 0.95 | 0.84 | 0.90 | 0.94 | 0.84 | 0.89 | 0.90 | 0.81 | 0.85 | 0.94 | 0.96 | 0.95 |
| **$1^{st}$T** | 0.91 | 0.90 | 0.90 | 0.94 | 0.94 | 0.94 | 0.96 | 0.97 | 0.97 | 0.99 | 0.96 | 0.97 |
| **5MH** | 0.83 | 0.88 | 0.85 | 0.89 | 0.93 | 0.91 | 0.79 | 0.94 | 0.86 | 0.85 | 0.90 | 0.87 |
| **4MH** | 0.87 | 0.88 | 0.88 | 0.91 | 0.89 | 0.90 | 0.81 | 0.92 | 0.86 | 0.89 | 0.84 | 0.86 |
| **3MH** | 0.93 | 0.95 | 0.94 | 0.93 | 0.93 | 0.93 | 0.90 | 0.95 | 0.93 | 0.91 | 0.94 | 0.93 |
| **2MH** | 0.94 | 0.96 | 0.95 | 0.94 | 0.91 | 0.92 | 0.95 | 0.95 | 0.95 | 0.96 | 0.94 | 0.95 |
| **1MH** | 0.89 | 0.88 | 0.89 | 0.86 | 0.93 | 0.90 | 0.88 | 0.95 | 0.92 | 0.93 | 0.95 | 0.94 |
| **MF** | 0.79 | 0.84 | 0.82 | 0.98 | 0.82 | 0.90 | 0.87 | 0.84 | 0.85 | 0.88 | 0.88 | 0.88 |
| **H** | 0.94 | 0.96 | 0.95 | 0.91 | 0.94 | 0.93 | 0.85 | 0.94 | 0.89 | 0.90 | 0.95 | 0.93 |

## 5.3. Discussion

The result of this experiment suggests that the increased weight by SBW, can notably rise pressures on the sole of the foot when other complicating agents, like the existence of disfigurements and restricted joint mobility but are controlled. The simulated body weight was achieved with the addition of 10, 20 and 30 kg of weight which increased foot pressures variables These findings were consistent for all regions of the foot. The result of the ANOVA displayed a noteworthy variation in foot measures, for the 10, 20 and 30 kg simulated body weight conditions compared with the normal group (0 kg). In general, an increase in the plantar measures was noticed, and alterations in gait pattern during simulated body weight gait was also observed when compared to the health category. The impacts of simulated body weight (four loads) were consistent at any foot measures given the simulations as shown in **(Figure 5.1 a, b, c, d, e).**

### 5.3.1. Force variable

The present study observed statistically significant increases in PF which occurred in the H, MF, 1MH, 2MH, and 3MH regions, for 10, 20 and 30 kg simulated body weights groups versus the NBW group (0 kg), as presented in **Table 5.1**. The findings of this study are clinically significant since areas of very high F or pressure under the foot are good indicators of potential damage being caused to the underlying tissue, particularly in symptomatic diabetic feet (Cavanagh et al., 1993).

This trend was particularly true in regions of the foot where relatively high loading typically occurs through gait, such as the H and forefoot (1MH, 2MH, and 3MH). Generally, the lower reliability was found in the typically less-loaded areas, such as the toes region. This study established a range of values of CV% for PTI beneath the toes region. Our findings were in absolute agreement with those of Gurney et al. (2008). Both studies found that the toes also showed the highest CV% across F parameter within all un-simulated and SBW.

### 5.3.2. Contact area variable

The higher foot contact area (CA) was shown within SBW groups (30, 20 and 10 kg) compared control counterparts (0 kg), as shown in **Table 5.2**. The largest CA with the insole system starting with the H region, 1MH and MF whereas, CA variables were slightly changed within the second toe zone. It is found that CA measure within the 3$^{rd}$-5$^{th}$T region in SBW groups, was a smaller value than in the control group.

This study established a range of values of CV% for CA beneath the toes region. Our findings were in absolute agreement with those of Gurney et al. (2008). Both studies found that the toes region had lower reliability, which was found in the typically less-loaded areas. The toes also showed the highest CV% across CA variable within all un-simulated and SBW.

### 5.3.3. Contact pressure variable

The 2MH, H, and 3MH regions respectively showed greater changes with simulated body weight, as displayed in **Table 5.3**. The variation between the averages of simulated body weights was significant ($P < 0.001$). The H region displayed differences in contact pressure (CP) values for the 10, 20 and 30 kg SBW group compared with the NBW group and thus appeared sensitive to smaller changes in body weight. The present experiment established no differences in mean CP within the 2$^{nd}$-5$^{th}$T and 1$^{st}$T regions. This result is consistent with observations reported by Martinez-Nova et al. (2008), who did not identify body mass as a statistically significant predictor of mean pressure within the lesser digits and 1$^{st}$T regions.

This study established a range of values of CV% for CP beneath the toes region. Our findings were in absolute agreement with those of Gurney et al. (2008). Both studies found that the lower reliability was found in the typically less-loaded areas, such as the toes region. The toes also showed the highest CV% across F parameter within all NBW and SBW.

### 5.3.4. Pressure time integral variable

The pressure time integral (PTI, kPa s) measure notably increased between the SBW groups compared with the NBW group. PTI variable was significantly different for all foot regions under SBW with the 10, 20 and 30 kg compared with the control groups (0 kg), as seen in **Table 5.4.** The H zone displayed differences in PTI for the 10, 20 and 30 kg simulated body weight states compared with the NBW (0 kg), and thus appeared sensitive to smaller changes in body weight. This may be due to a function of the increased mass alone. It would seem more likely for a difference in PTI to occur due to the larger SBW groups. This may also explain the absence of statistically significant differences in PTI for all simulated weights under the H, MF, 1MH, 2MH, 3MH, 4MH and 5MH, between the unweighted and weighted 30 kg. Also, these findings were in absolute agreement with those of McKay et al. (2017). Both studies found that the forefoot (MHs), H and MF had the biggest values of all the mentioned PTI measures.

This study established a range of values of CV% for PTI beneath the toes region. Our findings were in absolute agreement with those of Gurney et al. (2008). Both studies found that the toes region also showed the highest CV% across the F parameter within all un-simulated and SBW. Whereas, this region had lower reliability, which was found in the typically less-loaded areas, such as the toes region

### 5.3.5. Peak pressure variable

The measurement of peak pressure showed that statistically significant increases in peak pressure only occurred in the H, 2MH to 5MH, MF and 1$^{st}$T regions for 10, 20 and 30 kg simulated versus control group, and the MF, 2MH and 1$^{st}$T regions for 30 kg versus control group. These findings concurred with the study conducted by Vela et al. (1998). They found that statistically significant increases ($p \leq 0.05$) in PP under the H, MF, 1M, and lesser metatarsals (lesser toes) when 9.1 and 18.2kg of additional load were added to subjects.

In the present study, no statistically significant increases were found in PP during walking for the MF region with simulated body weight. However, this contrasts with Birtane and Tuna (2004), who reported that, out of six plantar regions, only the MF area recorded a statistically significant increase in peak plantar pressure when obese subjects (BMI 30.0-34.99 kg/m$^2$) were compared to non-obese controls. In contrast, previous studies by Hills et al. (2001) and Clarke (1981) found that healthy weight adults showed low correlation between body weight and PP under the feet. These studies did not consider PP across a range of anatomical locations and attributed the lack of relationship between weight and PP to either increased foot CA through the stance phase of gait or the distribution of high loads to larger anatomical areas of the foot. Contrary to the findings in adults, body weight was the main factor in the magnitude of pressure under the feet of school children aged between six and ten years (Hennig et al., 1994).

### 5.3.6. Repeatability of the F-Scan system

A capacitive pressure distribution insole system sampling at 100 Hz was used to collect plantar pressure patterns during in-shoe walking at a self-selected speed. Five parameters were investigated (Keijsers et al., 2010; Coda & Santos, 2015): force, contact area, contact pressure, pressure time integral and peak pressure, and these were investigated in ten areas of the foot using the FScan mask method of subdividing the foot into ten anatomical areas of interest. Individual means for all three repeated trials for each foot were calculated, and these values were used to calculate ICC for all parameters. The accuracy of foot plantar pressure was assessed with the mean value of three repeated trials within simulated body weight. These findings indicate that the insole system has displayed ‘good’ to ‘excellent’ reliability for the five analysis variables of F, CA, CP, PTI and PP for all ten evaluated areas, with the excluding of the mean pressure value for the second toe.

All insole systems produced the highest ICC values for pressure above 100 kPa. To summarise, an appropriate pressure measurement device is selected depending on the duration of loading, the magnitude of loading and the outcome variables sought. Medilogic and Tekscan are most effective between 200-300 kPa; Pedar performed well across all pressures (Price et al., 2014).

The findings of this study showed a commonly higher level of accuracy. Regions with typically high simulation characteristics, like the MF, demonstrated a greater level of precision in the ICC’s (>0.9) than lower simulated zones, such the $3^{rd}$-$5^{th}$T (<0.8). The conclusion of this research is that plantar pressure measurements can be applied in comparative assessments as the measures of repeatability are acceptable for the measurers and foot zones usually used in the study of clinical people like abnormal plantar pressure distribution with overweight and the obese foot or neuropathic diabetics.

According to Kernozek et al. (1996) and Putti et al. (2007) dynamic pedobarography is a constantly expanding field with new devices being designed and employed for various clinical applications. The repeatability of the earlier Pedar in-shoe systems was evaluated by Kernozek et al. (1996) and Putti et al. (2007). During the normal gait process, the heel initiates ground contact and the load is progressively spread across the various areas of the foot, of which the metatarsal heads region is one of the most important. The insole (Pedar-X ®) system showed a similar repeatability pattern for most foot areas considering the various parameters evaluated. When comparing the values of both feet (L and R), the majority of parameters showed similar repeatability for various foot regions. The results of the current study are consistent with that of Putti et al. (2007), and Ramanathan et al. (2010). Therefore, rise accuracy amidst testing periods within these foot zones as has been displayed by the result is very acceptable for clinical checking purposes. The influence of different foot orthotics on initial loading through gait were investigated by Cornwall and McPoil (1997). They pointed out that the between-trial accuracy ICC was markedly high for the forefoot areas but less so for other zones, which is in conformity with the outcomes for various measures. In addition, Gurney et al. (2008) determined the reliability of repeated plantar pressure distribution measurements during normal gait across multiple testing sessions. They established that the between-trial accuracy ICC was notably high for the centre metatarsal head zone, which is in accordance with the current outcomes for various measures.

## 5.4. Chapter summary

Dependant on the results offered in this chapter, the simulated body weight has achieved its intended purpose when using insole sets. The experiment investigated the effect of simulated body weight added at known intervals on foot variables (force, contact area, contact pressure, pressure time integral and peak pressure) in adult subjects during walking. The H, 2MH, 3MH and 1$^{st}$T regions were considered the main foot regions affected by SBW within all important pressure variable characteristics. The determined measures for variance (CV) may serve for power estimation in clinical intervention experiments. The 'good to excellent' ICC scores were gathered in most of the ten plantar pressure areas when investigating on foot variables. The findings of this experiment pointed out that an insole pressure system is a reliable tool for evaluating foot plantar forces and pressures through the walk. The plantar pressure measures can be used in relative assessments, as the measures of repeatability are favourable for the measures and foot zones generally utilised in the study of clinical people like neuropathic diabetics.

The next chapter of this study involves developing an innovative technique for the calculation of the centroid of the area of contact data during the moment of heel strike, midstance and toe-off phase of gait.

# 6. RESULT OF EXPERIMENT 3

## 6.1. Introduction

There are four main parts to this chapter. The first section (6.2) discusses the third experiment which studied the effect of simulated body weight on the centroid of the area of contact with heel strike, midstance and toe-off phases in adults. The section (6.2.1) introduces the centroid of the foot plantar in three phases (heel strike, midstance, and toe-off) during gait. The third section presents a discussion of the findings. Finally, the last section focuses on a summary of the chapter.

The enthusiasm for studying the human foot and gait loading to determine and manage impairments associated with various musculoskeletal, integumentary, and neurological disorders has intensified considerably in recent years. This type of research is particularly important in identifying the causes of diabetic foot ulceration and its treatment. In this chapter, the dynamic ground reaction force is captured with an insole pressure system. This chapter presents the results that answer objective three, which presents the method used to capture plantar pressure; an innovative technique for the calculation of the centroid of the area of contact captured by the developed system. The results and analysis are limited to three significant stages of the load phase: 1) Heel strike, where the heel is in initial contact with the substrate, 2) Midstance or the instant in the gait cycle where the swing leg passes the support leg, and 3) Toe-off or the instant before the plantar surface leaves the substrate. Thirty-one adults with a neutral foot type and a mean age of 37.55±6.92 years, mean body height of 1.74±0.08 m, body weight of 89.82±17.92 kg, and BMI of 29.7±5.1 kg/$m^2$ participated in the study. The chapter discusses the results of the study at centroid of the foot plantar during the stance phase of walk. This feature is related to the habits expressed by the participants' feet while carrying the simulated body weights. Two coordinate values (x-axis and y-axis) during the three phases are expressed as a percent of the total three trials studied.

## 6.2. The centroid of heel strike contact surface with the simulated body weight

The objective was to examine the impact of simulated body weight (SBW) within the participants' centre of the heel zone, by adding (10, 20, 30 kg). A sample of thirty-one adult males was tested. These subjects were grouped according to SBW and NBW to four groups: 0, 10, 20, and 30 kg. Participant characteristics are presented in **Table 3.3**.

### 6.2.1. X-axis coordinate of heel strike

The results show that, for the 31 subjects, the x-axis coordinate value increased at heel strike when moving with the simulated body weight. In all 4$^{th}$ groups (SBW and NBW), left foot and right foot values were almost the same values for each condition (0, 10, 20, and 30 kg). But overall, left and right foot values showed differences between the control (0 kg) and SBW (10, 20, and 30 kg) groups. The results for the x-axis coordinate values for both feet are given in **Table 6.1**.

The mean x-axis coordinate values under simulated body weight (30 kg) loads were higher in both feet, compared with the other weights of 20 kg and 10 kg and the un-simulated body weight. The x-axis coordinate mean values for NBW (0 kg) and SBW of 10, 20, 30 kg for the left foot were 5.54, 7.80, 9.67, and 11.77 mm, respectively. Moreover, the x-axis coordinate mean values for the right foot of 5.41, 7.73, 9.69, and 11.76 mm, respectively were obtained on the NBW (0 kg) and SBW with 10, 20, 30 kg.

**Table 6.1.** The mean value and SD for left and right foot in Heel strike phase (x-axis coordinate, mm)

| Heel strike-Left and right foot X-axis | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 5.97 | 0.29 | 5.10 | 0.46 | 7.47 | 0.47 | 7.87 | 0.57 | 10.33 | 0.21 | 8.85 | 0.26 | 11.90 | 0.75 | 11.90 | 1.14 |
| **2** | 5.77 | 0.49 | 5.30 | 0.78 | 8.20 | 0.36 | 7.97 | 0.25 | 9.37 | 0.58 | 9.93 | 0.06 | 11.75 | 0.15 | 11.75 | 0.23 |
| **3** | 5.77 | 0.49 | 5.30 | 0.78 | 8.20 | 0.36 | 7.97 | 0.25 | 9.84 | 0.58 | 9.93 | 0.06 | 11.47 | 0.15 | 11.47 | 0.23 |
| **4** | 6.30 | 0.35 | 5.40 | 0.17 | 8.50 | 0.10 | 8.00 | 0.10 | 9.50 | 0.10 | 10.60 | 0.60 | 12.14 | 0.32 | 12.14 | 0.17 |
| **5** | 5.50 | 0.87 | 6.10 | 0.40 | 7.53 | 0.06 | 7.77 | 0.67 | 9.27 | 0.31 | 9.07 | 0.55 | 11.50 | 0.26 | 11.50 | 0.64 |
| **6** | 5.83 | 0.21 | 6.03 | 1.45 | 7.63 | 1.17 | 7.87 | 0.15 | 9.47 | 0.06 | 10.23 | 0.80 | 11.85 | 0.26 | 11.85 | 0.80 |
| **7** | 6.03 | 0.06 | 3.33 | 0.06 | 8.53 | 0.55 | 7.53 | 0.55 | 9.38 | 0.17 | 9.30 | 0.17 | 11.67 | 0.35 | 11.67 | 0.35 |
| **8** | 5.87 | 0.25 | 5.50 | 0.10 | 8.03 | 0.60 | 7.70 | 0.17 | 9.87 | 0.32 | 7.83 | 0.06 | 11.23 | 0.40 | 11.23 | 0.40 |
| **9** | 5.33 | 0.06 | 3.33 | 0.06 | 7.60 | 0.53 | 7.60 | 0.53 | 10.43 | 0.83 | 9.43 | 0.83 | 11.53 | 0.06 | 11.53 | 0.06 |
| **10** | 5.13 | 0.57 | 5.90 | 0.26 | 8.03 | 0.29 | 7.93 | 0.21 | 9.57 | 0.06 | 10.23 | 0.15 | 11.71 | 0.15 | 11.71 | 0.84 |
| **11** | 5.33 | 0.06 | 5.33 | 0.06 | 7.60 | 0.53 | 7.60 | 0.53 | 9.43 | 0.83 | 10.43 | 0.83 | 11.65 | 0.06 | 11.65 | 0.06 |
| **12** | 5.90 | 0.20 | 5.93 | 0.38 | 8.00 | 0.10 | 7.50 | 0.26 | 9.43 | 1.10 | 9.93 | 0.86 | 11.73 | 0.51 | 11.73 | 0.44 |
| **13** | 6.33 | 0.06 | 5.33 | 0.06 | 7.60 | 0.53 | 7.60 | 0.53 | 9.84 | 0.83 | 10.43 | 0.83 | 11.85 | 0.06 | 11.85 | 0.06 |
| **14** | 5.33 | 0.06 | 5.63 | 0.21 | 7.60 | 0.53 | 8.90 | 0.10 | 9.43 | 0.83 | 9.97 | 0.38 | 11.65 | 0.06 | 11.65 | 0.21 |
| **15** | 5.83 | 0.46 | 5.33 | 0.00 | 8.10 | 0.20 | 7.33 | 1.70 | 9.49 | 0.26 | 10.07 | 0.74 | 12.00 | 0.95 | 12.00 | 0.50 |
| **16** | 5.33 | 0.06 | 5.33 | 0.06 | 7.60 | 0.53 | 7.60 | 0.53 | 9.43 | 0.83 | 10.43 | 0.83 | 11.75 | 0.06 | 11.75 | 0.06 |
| **17** | 5.33 | 0.25 | 6.73 | 0.49 | 7.83 | 0.58 | 7.67 | 0.61 | 10.23 | 0.47 | 10.10 | 0.30 | 12.03 | 0.06 | 12.03 | 0.17 |
| **18** | 5.20 | 0.26 | 5.37 | 0.59 | 8.03 | 0.12 | 8.90 | 0.48 | 10.03 | 0.15 | 9.93 | 0.15 | 11.92 | 0.03 | 11.92 | 0.10 |
| **19** | 5.07 | 0.70 | 6.93 | 0.15 | 8.00 | 0.61 | 7.43 | 0.29 | 9.54 | 0.35 | 9.43 | 0.25 | 11.57 | 0.29 | 11.57 | 0.32 |
| **20** | 5.33 | 0.06 | 5.33 | 0.06 | 8.53 | 0.55 | 7.53 | 0.55 | 9.53 | 0.17 | 9.30 | 0.17 | 11.47 | 0.35 | 11.37 | 0.35 |
| **21** | 5.33 | 0.06 | 5.33 | 0.06 | 7.60 | 0.53 | 7.68 | 0.53 | 9.43 | 0.83 | 9.94 | 0.83 | 11.53 | 0.06 | 11.53 | 0.06 |
| **22** | 5.00 | 0.10 | 6.33 | 0.03 | 8.30 | 1.41 | 7.90 | 0.10 | 10.20 | 0.53 | 10.07 | 0.55 | 12.03 | 0.45 | 12.03 | 0.32 |
| **23** | 5.03 | 0.45 | 5.40 | 0.40 | 7.63 | 0.47 | 7.33 | 0.45 | 9.90 | 0.85 | 10.43 | 0.12 | 12.59 | 0.62 | 12.59 | 0.70 |
| **24** | 5.37 | 0.59 | 5.67 | 0.12 | 7.87 | 0.51 | 8.03 | 0.58 | 9.29 | 0.06 | 10.11 | 0.87 | 12.30 | 0.36 | 12.30 | 0.42 |
| **25** | 5.40 | 0.20 | 6.03 | 0.20 | 7.53 | 0.12 | 7.23 | 0.32 | 9.97 | 0.65 | 9.23 | 1.15 | 12.03 | 0.32 | 12.03 | 0.65 |
| **26** | 5.33 | 0.06 | 3.33 | 0.06 | 7.60 | 0.53 | 7.53 | 0.55 | 9.43 | 0.83 | 9.30 | 0.17 | 11.53 | 0.06 | 11.53 | 0.35 |
| **27** | 5.50 | 0.10 | 5.40 | 0.35 | 8.23 | 0.23 | 7.77 | 0.23 | 9.70 | 0.36 | 9.57 | 0.29 | 11.57 | 0.12 | 11.47 | 0.10 |
| **28** | 5.48 | 0.26 | 5.63 | 0.31 | 7.53 | 0.06 | 7.23 | 0.06 | 9.60 | 0.26 | 7.86 | 0.21 | 11.73 | 0.38 | 11.73 | 1.59 |
| **29** | 5.43 | 0.64 | 5.03 | 0.49 | 5.47 | 0.32 | 7.43 | 0.12 | 9.83 | 0.31 | 9.80 | 0.26 | 12.00 | 0.17 | 12.10 | 0.17 |
| **30** | 6.13 | 0.32 | 5.97 | 0.12 | 7.87 | 0.23 | 7.60 | 0.35 | 9.17 | 0.25 | 9.98 | 0.10 | 11.83 | 0.25 | 11.80 | 0.00 |
| **31** | 5.13 | 0.47 | 5.10 | 0.42 | 7.47 | 0.06 | 7.63 | 0.15 | 9.97 | 0.15 | 8.65 | 0.15 | 11.20 | 0.82 | 11.20 | 0.36 |
| **mean** | 5.54 | | 5.41 | | 7.80 | | 7.73 | | 9.67 | | 9.69 | | 11.77 | | 11.76 | |

### 6.2.2. Y-axis coordinate of heel-strike

The results show that the y-axis coordinate values increased at heel strike for the 31 subjects moving with simulated body weight. In all four groups (0, 10, 20, and 30 kg) left foot and right foot values were almost the same values for each condition. However, left foot and right values did show differences between the normal state (0 kg) and simulated (10, 20, and 30 kg) states. The results for y-axis coordinate values for both feet are given in **Table 6.2**.

The NBW group (0 kg) had a lower y-axis coordinate mean values than the SBW group (10, 20, 30 kg) for both feet. The y-axis coordinates mean values for the NBW (0 kg) and SBW with 10, 20, 30 kg were 6.17, 8.18, 9.67, and 11.97 mm, respectively for the left foot. In addition, the y-axis coordinates mean values based on the NBW (0 kg) and SBW with 10, 20, 30kg for the right foot were 6.20, 8.17, 10.10, and 11.96 mm, respectively.

**Table 6.2.** The mean value and SD for left and right foot in Heel strike phase (y-axis coordinate, mm)

| Heel strike- Left and right foot Y-axis | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 6.50 | 0.69 | 6.07 | 0.40 | 8.97 | 0.75 | 8.77 | 0.18 | 10.23 | 0.21 | 10.47 | 8.87 | 11.43 | 0.76 | 11.45 | 0.55 |
| **2** | 6.23 | 1.08 | 6.33 | 0.55 | 8.60 | 0.20 | 7.95 | 0.17 | 9.83 | 0.31 | 9.77 | 0.26 | 11.53 | 0.49 | 11.52 | 0.12 |
| **3** | 6.23 | 1.08 | 6.33 | 0.55 | 8.60 | 0.20 | 8.50 | 0.17 | 9.83 | 0.31 | 10.70 | 0.26 | 11.53 | 0.49 | 11.53 | 0.12 |
| **4** | 6.20 | 0.00 | 5.67 | 0.67 | 8.10 | 0.10 | 8.13 | 0.52 | 10.22 | 0.25 | 10.20 | 0.30 | 11.73 | 0.24 | 11.69 | 0.17 |
| **5** | 5.73 | 0.59 | 6.67 | 0.49 | 7.77 | 0.42 | 8.60 | 0.92 | 9.40 | 0.26 | 9.85 | 0.96 | 11.40 | 0.20 | 11.42 | 0.06 |
| **6** | 6.30 | 0.61 | 5.83 | 1.84 | 8.50 | 0.95 | 8.07 | 0.32 | 9.77 | 0.31 | 10.92 | 1.14 | 12.03 | 0.37 | 11.99 | 0.90 |
| **7** | 6.73 | 0.23 | 6.73 | 0.23 | 8.07 | 0.81 | 8.07 | 0.81 | 9.13 | 0.71 | 10.01 | 0.71 | 12.15 | 0.78 | 12.05 | 0.78 |
| **8** | 5.93 | 0.12 | 6.53 | 0.06 | 8.13 | 0.67 | 8.27 | 0.32 | 9.70 | 0.53 | 9.73 | 0.59 | 11.67 | 0.23 | 11.57 | 0.26 |
| **9** | 5.73 | 0.23 | 5.78 | 0.23 | 8.22 | 0.10 | 8.00 | 0.10 | 9.57 | 0.15 | 10.57 | 0.15 | 12.80 | 0.48 | 12.79 | 0.48 |
| **10** | 6.30 | 0.50 | 6.70 | 0.36 | 8.60 | 0.10 | 8.07 | 0.21 | 9.27 | 0.21 | 10.37 | 0.21 | 11.97 | 0.12 | 11.97 | 0.40 |
| **11** | 5.73 | 0.23 | 5.73 | 0.23 | 8.11 | 0.10 | 8.11 | 0.10 | 9.86 | 0.15 | 10.36 | 0.15 | 12.80 | 0.48 | 12.80 | 0.48 |
| **12** | 5.93 | 0.50 | 6.87 | 0.35 | 7.83 | 0.15 | 8.43 | 0.15 | 9.13 | 0.91 | 9.77 | 0.61 | 11.86 | 0.29 | 11.82 | 0.38 |
| **13** | 5.73 | 0.23 | 5.73 | 0.23 | 8.00 | 0.10 | 7.89 | 0.10 | 9.57 | 0.15 | 9.76 | 0.15 | 12.33 | 0.48 | 12.33 | 0.48 |
| **14** | 5.73 | 0.23 | 6.17 | 0.06 | 8.12 | 0.10 | 7.87 | 0.25 | 9.87 | 0.15 | 10.27 | 0.23 | 12.50 | 0.48 | 12.50 | 0.58 |
| **15** | 5.83 | 0.29 | 6.73 | 1.00 | 8.03 | 0.15 | 7.83 | 1.22 | 9.53 | 0.25 | 10.10 | 9.27 | 11.86 | 0.06 | 11.83 | 0.33 |
| **16** | 5.73 | 0.23 | 5.73 | 0.23 | 8.20 | 0.10 | 8.10 | 0.10 | 9.57 | 0.15 | 9.76 | 0.15 | 12.80 | 0.48 | 12.81 | 0.48 |
| **17** | 6.07 | 0.56 | 6.70 | 1.31 | 8.90 | 1.59 | 7.85 | 0.62 | 9.67 | 0.12 | 9.82 | 0.82 | 12.03 | 0.35 | 12.01 | 0.17 |
| **18** | 6.73 | 0.23 | 5.57 | 0.06 | 7.65 | 0.42 | 7.89 | 0.35 | 10.30 | 0.44 | 10.03 | 0.15 | 11.53 | 0.06 | 11.53 | 0.25 |
| **19** | 5.99 | 0.10 | 6.27 | 0.31 | 8.03 | 0.55 | 8.63 | 0.91 | 9.87 | 0.48 | 10.10 | 0.20 | 11.87 | 0.25 | 11.87 | 0.12 |
| **20** | 6.73 | 0.23 | 5.73 | 0.23 | 8.07 | 0.81 | 8.07 | 0.81 | 9.13 | 0.71 | 10.13 | 0.71 | 12.50 | 0.78 | 12.60 | 0.78 |
| **21** | 6.73 | 0.23 | 6.73 | 0.23 | 8.12 | 0.10 | 8.02 | 0.10 | 9.67 | 0.15 | 10.76 | 0.15 | 12.10 | 0.48 | 12.20 | 0.48 |
| **22** | 5.70 | 0.40 | 5.73 | 0.47 | 7.53 | 0.81 | 8.85 | 0.36 | 10.00 | 0.62 | 10.17 | 0.92 | 11.82 | 0.83 | 11.83 | 0.45 |
| **23** | 6.47 | 0.18 | 6.53 | 0.12 | 8.03 | 0.21 | 8.27 | 0.50 | 9.57 | 0.38 | 9.37 | 0.51 | 11.70 | 0.38 | 11.60 | 0.45 |
| **24** | 6.20 | 0.79 | 6.80 | 0.70 | 8.90 | 0.53 | 7.60 | 0.81 | 9.17 | 1.22 | 10.37 | 0.68 | 11.86 | 0.66 | 11.86 | 0.46 |
| **25** | 6.12 | 0.35 | 5.13 | 0.70 | 8.37 | 0.06 | 8.57 | 0.67 | 9.77 | 0.90 | 9.86 | 0.99 | 12.10 | 0.46 | 12.04 | 0.65 |
| **26** | 5.73 | 0.23 | 5.73 | 0.23 | 8.00 | 0.10 | 8.07 | 0.81 | 9.57 | 0.15 | 9.91 | 0.71 | 12.00 | 0.48 | 12.10 | 0.78 |
| **27** | 6.63 | 0.32 | 6.57 | 0.45 | 8.20 | 0.35 | 7.13 | 0.12 | 9.70 | 0.10 | 9.83 | 0.29 | 12.07 | 0.32 | 12.00 | 0.47 |
| **28** | 6.00 | 0.32 | 6.70 | 0.66 | 8.13 | 0.93 | 8.80 | 0.25 | 9.63 | 0.81 | 10.20 | 0.26 | 11.87 | 0.15 | 11.85 | 0.76 |
| **29** | 6.83 | 0.90 | 6.00 | 0.36 | 8.27 | 0.31 | 8.13 | 0.21 | 9.73 | 0.51 | 10.03 | 0.42 | 11.75 | 0.25 | 11.71 | 0.45 |
| **30** | 6.17 | 0.67 | 6.10 | 0.00 | 7.57 | 0.45 | 8.43 | 0.12 | 9.93 | 0.06 | 9.93 | 0.00 | 11.73 | 0.15 | 11.70 | 0.17 |
| **31** | 6.50 | 0.26 | 6.30 | 0.00 | 8.03 | 0.23 | 8.37 | 0.40 | 9.64 | 0.42 | 9.97 | 0.21 | 11.72 | 1.01 | 11.71 | 0.64 |
| **mean** | 6.11 | | 6.20 | | 8.18 | | 8.17 | | 9.67 | | 10.10 | | 11.97 | | 11.96 | |

## 6.3. The centroid of midstance contact surface for the simulated body weight

For all 31 subjects, the x-axis coordinate of midstance changes when moving. The maximum and minimum distributions of the left heel in the midstance phase are similar to those observed for the right foot, as shown in **Table 6.3**.

The greater mean x-axis coordinate value for both left and right midstance within the SBW group (10, 20, 30 kg) were found compared with the mean x-axis coordinate in midstance phase for both left and right value with NBW (0 kg) group.

### 6.3.1. X-axis coordinate of midstance

The mean values of the maximum x-axis coordinate for both left and right feet within the SBW sets were 4.53 and 4.46 mm for the 10 kg; 5.48 and 5.48 mm for 20 kg; and 6.60 and 6.58 mm with 30 kg. The mean values for x-axis coordinate, both left and right value, with NBW were 2.99 and 2.98 mm, respectively.

**Table 6.3.** The mean value and SD for left and right foot with midstance phase (x-axis coordinate, mm)

| Midstance- Left and right foot X-axis | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 3.63 | 0.96 | 3.63 | 0.96 | 4.67 | 0.75 | 4.62 | 0.75 | 5.70 | 0.17 | 5.70 | 0.06 | 6.90 | 0.95 | 6.90 | 0.95 |
| **2** | 3.07 | 0.15 | 3.07 | 0.15 | 4.80 | 0.10 | 4.80 | 0.10 | 5.33 | 0.40 | 5.33 | 0.06 | 6.73 | 0.38 | 6.73 | 0.38 |
| **3** | 2.83 | 0.23 | 2.83 | 0.23 | 4.70 | 0.10 | 4.70 | 0.10 | 5.23 | 0.29 | 5.54 | 0.21 | 6.87 | 0.31 | 6.87 | 0.31 |
| **4** | 2.33 | 0.06 | 2.33 | 0.15 | 4.53 | 0.15 | 4.41 | 0.12 | 5.43 | 0.06 | 5.43 | 0.10 | 6.87 | 0.31 | 6.80 | 0.38 |
| **5** | 2.27 | 0.25 | 2.27 | 0.25 | 4.40 | 0.53 | 4.38 | 0.53 | 5.07 | 0.21 | 5.07 | 0.95 | 6.97 | 0.15 | 6.97 | 0.62 |
| **6** | 2.50 | 0.82 | 2.50 | 0.09 | 4.13 | 0.38 | 4.13 | 0.15 | 5.10 | 0.10 | 5.10 | 0.15 | 6.70 | 0.20 | 6.70 | 0.44 |
| **7** | 3.90 | 0.26 | 3.90 | 0.96 | 4.20 | 0.95 | 4.11 | 0.75 | 5.07 | 0.06 | 5.07 | 0.06 | 6.83 | 0.27 | 6.79 | 0.95 |
| **8** | 2.83 | 0.31 | 2.83 | 0.35 | 4.30 | 0.00 | 4.30 | 0.00 | 5.57 | 0.32 | 5.57 | 0.10 | 6.47 | 0.15 | 6.47 | 0.06 |
| **9** | 2.63 | 1.96 | 2.61 | 0.96 | 4.47 | 0.75 | 4.47 | 0.75 | 5.70 | 0.17 | 5.70 | 0.06 | 6.90 | 0.95 | 6.90 | 0.95 |
| **10** | 2.83 | 0.23 | 2.80 | 0.23 | 4.74 | 0.10 | 4.74 | 0.56 | 5.23 | 0.29 | 5.23 | 0.46 | 6.87 | 0.31 | 6.87 | 0.40 |
| **11** | 2.83 | 0.23 | 2.93 | 0.23 | 4.70 | 0.10 | 4.77 | 0.10 | 5.23 | 0.29 | 5.21 | 0.21 | 6.87 | 0.31 | 6.79 | 0.31 |
| **12** | 2.23 | 0.40 | 2.22 | 0.06 | 4.40 | 0.53 | 4.40 | 0.40 | 5.53 | 0.06 | 5.53 | 0.29 | 6.17 | 0.40 | 6.17 | 0.52 |
| **13** | 3.23 | 0.12 | 3.03 | 0.12 | 4.87 | 0.31 | 4.07 | 0.31 | 5.70 | 0.17 | 5.67 | 0.70 | 6.10 | 0.40 | 6.12 | 0.40 |
| **14** | 2.83 | 0.23 | 2.83 | 0.23 | 4.70 | 0.10 | 4.70 | 0.10 | 5.23 | 0.29 | 5.20 | 0.21 | 6.87 | 0.31 | 6.87 | 0.31 |
| **15** | 3.43 | 0.72 | 3.43 | 0.00 | 4.60 | 0.10 | 4.60 | 0.80 | 5.70 | 0.10 | 5.87 | 1.81 | 6.83 | 0.25 | 6.83 | 0.10 |
| **16** | 2.83 | 0.23 | 2.90 | 0.23 | 4.70 | 0.10 | 4.70 | 0.10 | 5.23 | 0.29 | 5.23 | 0.21 | 6.87 | 0.31 | 6.80 | 0.31 |
| **17** | 3.53 | 0.06 | 3.53 | 0.00 | 4.27 | 0.25 | 4.22 | 0.38 | 5.90 | 0.00 | 5.90 | 0.10 | 6.53 | 0.06 | 6.53 | 0.06 |
| **18** | 2.30 | 0.44 | 2.28 | 0.42 | 4.53 | 0.64 | 4.53 | 0.23 | 5.63 | 0.46 | 5.63 | 0.37 | 6.33 | 0.15 | 6.33 | 0.31 |
| **19** | 2.60 | 0.40 | 2.60 | 0.96 | 4.73 | 0.12 | 4.73 | 0.75 | 5.97 | 0.72 | 5.91 | 0.06 | 6.33 | 0.68 | 6.33 | 0.95 |
| **20** | 3.63 | 0.96 | 3.60 | 0.96 | 4.07 | 0.75 | 4.07 | 0.75 | 5.65 | 0.17 | 5.60 | 0.06 | 6.89 | 0.95 | 6.89 | 0.95 |
| **21** | 2.83 | 0.23 | 2.73 | 0.23 | 4.00 | 0.40 | 4.00 | 0.40 | 5.17 | 0.38 | 5.17 | 0.83 | 6.17 | 0.32 | 6.17 | 0.32 |
| **22** | 3.07 | 0.15 | 3.07 | 0.15 | 4.80 | 0.10 | 4.80 | 0.10 | 5.53 | 0.06 | 5.53 | 0.06 | 6.73 | 0.38 | 6.73 | 0.38 |
| **23** | 3.53 | 0.06 | 3.53 | 0.06 | 4.27 | 0.25 | 4.27 | 0.25 | 5.90 | 0.00 | 5.90 | 0.50 | 6.53 | 0.06 | 6.43 | 0.06 |
| **24** | 3.23 | 0.12 | 3.23 | 0.31 | 4.87 | 0.31 | 4.87 | 0.23 | 5.70 | 0.17 | 5.70 | 0.21 | 6.10 | 0.40 | 6.10 | 0.23 |
| **25** | 2.60 | 0.40 | 2.60 | 0.06 | 4.73 | 0.12 | 4.65 | 0.61 | 5.97 | 0.72 | 5.97 | 0.64 | 6.33 | 0.68 | 6.33 | 1.81 |
| **26** | 2.80 | 1.48 | 2.80 | 0.56 | 4.23 | 0.41 | 4.23 | 0.06 | 5.43 | 0.74 | 5.23 | 0.14 | 6.93 | 0.24 | 6.93 | 0.47 |
| **27** | 3.63 | 0.96 | 3.60 | 0.62 | 4.07 | 0.75 | 4.03 | 0.55 | 5.70 | 0.17 | 5.68 | 0.79 | 6.90 | 0.95 | 6.88 | 0.67 |
| **28** | 2.77 | 0.12 | 2.72 | 0.06 | 4.87 | 0.32 | 4.87 | 0.81 | 5.00 | 0.17 | 5.00 | 0.73 | 6.27 | 0.06 | 6.27 | 1.16 |
| **29** | 3.87 | 0.15 | 3.87 | 0.10 | 4.27 | 0.15 | 4.17 | 0.15 | 5.87 | 0.15 | 5.87 | 0.53 | 6.17 | 0.06 | 6.17 | 0.31 |
| **30** | 2.83 | 0.23 | 2.83 | 0.50 | 4.88 | 0.40 | 4.08 | 0.10 | 5.17 | 0.38 | 5.17 | 0.36 | 6.17 | 0.32 | 6.17 | 0.38 |
| **31** | 3.23 | 0.38 | 3.23 | 0.15 | 4.93 | 0.06 | 4.93 | 0.42 | 5.23 | 0.21 | 5.21 | 0.58 | 6.40 | 0.40 | 6.11 | 0.85 |
| **mean** | 2.99 | | 2.98 | | 4.53 | | 4.46 | | 5.48 | | 5.48 | | 6.60 | | 6.58 | |

### 6.3.2. Y-axis coordinate of midstance

The y-axis coordinate of midstance changes with movement for all 31 subjects. The maximum and minimum distributions of the left heel in the midstance phase are similar to those observed for the right foot, as shown in **Table 6.4**.

The greatest mean y-axis coordinate of values for left and right midstance were found in the SBW group (10, 20, 30 kg) compared with the y-axis coordinate in midstance phase for both left and right values with the NBW (0 kg) group.

The mean values of the maximum y-axis coordinate for both left and right feet in the SBW sets were 4.43 and 4.39 mm for the 10 kg; 5.42 and 5.40 mm for 20 kg, and 6.41 and 6.36 mm for 30 kg. The mean values for the y-axis coordinate, both left and right values, with for NBW were 3.05, 3.05 mm.

**Table 6.4.** The of mean value and SD for left and right foot in midstance phase (y- axis coordinate, mm)

| | Midstance- Left and right foot Y-axis | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 3.76 | 0.12 | 3.76 | 0.12 | 4.23 | 0.06 | 4.03 | 0.06 | 5.17 | 0.23 | 5.16 | 0.23 | 6.73 | 0.67 | 6.45 | 0.67 |
| **2** | 3.40 | 0.61 | 3.38 | 0.61 | 4.17 | 0.06 | 4.17 | 0.06 | 5.30 | 0.53 | 5.30 | 0.53 | 6.00 | 0.35 | 6.10 | 0.35 |
| **3** | 2.00 | 0.55 | 2.00 | 0.55 | 4.93 | 0.21 | 4.88 | 0.21 | 5.23 | 0.40 | 5.23 | 0.40 | 6.07 | 0.12 | 6.01 | 0.12 |
| **4** | 3.67 | 0.31 | 3.67 | 0.12 | 4.70 | 0.35 | 4.70 | 0.10 | 5.43 | 0.12 | 5.43 | 0.46 | 6.07 | 0.12 | 6.12 | 0.35 |
| **5** | 3.00 | 0.17 | 3.00 | 0.17 | 4.03 | 0.95 | 4.03 | 0.95 | 5.07 | 0.32 | 5.02 | 0.17 | 6.73 | 0.84 | 6.65 | 0.12 |
| **6** | 3.80 | 0.36 | 3.78 | 0.15 | 4.30 | 0.17 | 4.30 | 0.15 | 5.83 | 0.12 | 5.83 | 0.10 | 6.77 | 0.57 | 6.67 | 0.50 |
| **7** | 3.10 | 0.46 | 3.10 | 0.12 | 4.10 | 0.86 | 4.12 | 0.06 | 5.40 | 0.10 | 5.37 | 0.23 | 6.10 | 0.31 | 5.46 | 0.67 |
| **8** | 2.37 | 0.81 | 2.37 | 0.33 | 4.57 | 0.15 | 4.50 | 0.00 | 5.97 | 0.42 | 5.97 | 0.46 | 6.87 | 0.06 | 6.87 | 0.21 |
| **9** | 3.76 | 0.12 | 3.72 | 0.12 | 4.23 | 0.06 | 4.23 | 0.06 | 5.17 | 0.23 | 5.17 | 0.23 | 6.73 | 0.67 | 6.73 | 0.67 |
| **10** | 2.00 | 0.52 | 2.00 | 0.42 | 4.93 | 0.21 | 4.93 | 0.46 | 5.23 | 0.40 | 5.23 | 0.62 | 6.07 | 0.12 | 6.02 | 0.95 |
| **11** | 2.00 | 0.55 | 2.20 | 1.55 | 4.93 | 0.21 | 4.93 | 0.21 | 5.23 | 0.40 | 5.20 | 0.40 | 6.07 | 0.12 | 6.07 | 0.12 |
| **12** | 2.73 | 0.04 | 2.73 | 0.69 | 4.03 | 0.95 | 4.03 | 0.29 | 5.07 | 0.15 | 5.07 | 0.87 | 6.67 | 0.81 | 6.67 | 0.23 |
| **13** | 3.93 | 0.38 | 3.91 | 0.38 | 4.20 | 0.70 | 4.10 | 0.70 | 5.90 | 0.69 | 5.89 | 0.69 | 6.00 | 0.15 | 5.89 | 0.15 |
| **14** | 2.00 | 0.55 | 1.99 | 0.55 | 4.93 | 0.21 | 4.93 | 0.21 | 5.23 | 0.40 | 5.34 | 0.40 | 6.07 | 0.12 | 6.07 | 0.12 |
| **15** | 3.53 | 5.86 | 3.53 | 0.18 | 4.20 | 0.08 | 4.11 | 1.81 | 5.20 | 6.08 | 5.20 | 0.40 | 6.57 | 0.17 | 6.55 | 0.91 |
| **16** | 2.00 | 0.55 | 2.00 | 0.55 | 4.93 | 0.21 | 4.83 | 0.21 | 5.23 | 0.40 | 5.23 | 0.40 | 6.07 | 0.12 | 6.07 | 0.12 |
| **17** | 3.67 | 0.06 | 3.63 | 0.06 | 4.17 | 0.50 | 4.17 | 0.10 | 5.33 | 1.67 | 5.31 | 0.42 | 6.33 | 0.15 | 6.33 | 0.06 |
| **18** | 2.33 | 0.49 | 2.33 | 0.25 | 4.07 | 0.06 | 4.02 | 0.37 | 5.90 | 0.10 | 5.90 | 0.06 | 6.90 | 0.17 | 6.90 | 1.40 |
| **19** | 3.30 | 0.52 | 3.32 | 0.12 | 4.93 | 0.10 | 4.93 | 0.06 | 5.30 | 0.26 | 5.02 | 0.23 | 6.40 | 0.36 | 6.40 | 0.67 |
| **20** | 3.76 | 0.12 | 3.71 | 0.12 | 4.23 | 0.06 | 4.23 | 0.06 | 5.19 | 0.23 | 5.19 | 0.23 | 6.73 | 0.67 | 6.73 | 0.67 |
| **21** | 2.00 | 0.55 | 2.00 | 0.55 | 4.33 | 0.83 | 4.04 | 0.83 | 5.80 | 0.10 | 5.80 | 0.10 | 6.70 | 0.66 | 6.69 | 0.66 |
| **22** | 3.40 | 0.61 | 3.40 | 0.61 | 4.17 | 0.06 | 4.17 | 0.06 | 5.43 | 0.23 | 5.33 | 0.53 | 6.00 | 0.35 | 6.00 | 0.35 |
| **23** | 3.67 | 0.06 | 3.67 | 0.06 | 4.17 | 0.50 | 4.17 | 0.50 | 5.33 | 1.67 | 5.33 | 0.67 | 6.33 | 0.15 | 6.11 | 0.15 |
| **24** | 3.93 | 0.38 | 3.93 | 0.12 | 4.20 | 0.70 | 4.20 | 0.21 | 5.90 | 0.69 | 5.90 | 0.98 | 6.00 | 1.15 | 6.00 | 0.35 |
| **25** | 3.30 | 0.52 | 3.30 | 0.06 | 4.93 | 0.10 | 4.93 | 0.64 | 5.30 | 0.26 | 5.30 | 0.81 | 6.40 | 0.36 | 6.40 | 0.72 |
| **26** | 3.53 | 0.69 | 3.53 | 0.53 | 4.20 | 0.01 | 4.20 | 0.14 | 5.07 | 0.68 | 5.07 | 0.66 | 6.07 | 0.21 | 6.07 | 0.74 |
| **27** | 3.76 | 0.12 | 3.72 | 0.00 | 4.23 | 0.06 | 4.20 | 0.79 | 5.17 | 0.23 | 5.12 | 0.55 | 6.73 | 0.67 | 6.68 | 0.63 |
| **28** | 2.43 | 0.24 | 2.41 | 0.15 | 4.97 | 1.24 | 4.97 | 0.73 | 5.20 | 0.70 | 5.20 | 0.21 | 6.57 | 0.06 | 6.52 | 0.08 |
| **29** | 3.73 | 0.31 | 3.73 | 0.98 | 4.55 | 0.53 | 4.55 | 0.53 | 5.73 | 0.31 | 5.68 | 0.59 | 6.67 | 0.23 | 6.67 | 0.12 |
| **30** | 2.00 | 0.55 | 2.00 | 0.44 | 4.33 | 0.83 | 4.11 | 0.36 | 5.80 | 0.10 | 5.80 | 0.55 | 6.70 | 0.66 | 6.70 | 0.78 |
| **31** | 2.63 | 0.64 | 2.63 | 0.76 | 4.50 | 0.17 | 4.50 | 0.58 | 5.80 | 0.36 | 5.80 | 0.62 | 6.57 | 0.88 | 6.57 | 0.71 |
| **mean** | 3.05 | | 3.05 | | 4.43 | | 4.39 | | 5.42 | | 5.40 | | 6.41 | | 6.36 | |

## 6.4. The centroid of toe-off contact surface for simulated body weight

The objective was to investigate the influence of SBW on the participants' centre of toe-off zone by adding 10, 20, 30 kg. Samples of 31 adult males were tested. These subjects were grouped into four groups according to SBW and NBW: 0, 10, 20, and 30 kg. Participant characteristics are shown in **Table 3.3**.

### 6.4.1. X-axis coordinate of toe-off

The results show that the x-axis coordinate values increased at toe-off for the 31 subjects moving with simulated body weight. In all four groups (0, 10, 20, and 30 kg) left foot and right foot values were almost the same values for each condition. However, left foot and right foot values did show differences between NBW (0 kg) and SBW with 10, 20, and 30 kg weights. The results for x-axis coordinate value for both feet are given in **Table 6.5**.

Compared with the other simulated weights (20 and 10 kg) and the NBW (0 kg), the mean x-axis coordinate values under SBW of 30 kg loads were higher for both feet. The x-axis coordinate mean values for NBW (0 kg) and SBW of 10, 20, 30 kg for the left foot were 6.05, 7.97, 9.72, and 11.58 mm, respectively. X-axis coordinate mean values for the right foot were 6.04, 7.96, 9.71, and 11.57 mm, respectively based on the NBW (0 kg) and SBW of 10, 20, 30 kg.

**Table 6.5.** The mean value and SD for left and right foot in toe-off phase (x-axis coordinate, mm)

| **Toe-off- Left and right foot X-axis** | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 6.13 | 0.92 | 6.13 | 0.74 | 8.83 | 1.01 | 8.83 | 0.98 | 9.78 | 0.64 | 9.70 | 0.06 | 11.67 | 0.81 | 11.67 | 0.85 |
| **2** | 6.80 | 1.82 | 6.80 | 0.26 | 7.03 | 0.15 | 7.33 | 0.46 | 9.57 | 0.81 | 9.52 | 0.55 | 11.80 | 0.92 | 11.80 | 0.32 |
| **3** | 6.80 | 1.82 | 6.07 | 0.25 | 7.03 | 0.15 | 7.30 | 0.46 | 9.57 | 0.81 | 9.53 | 0.55 | 11.33 | 0.68 | 11.33 | 0.83 |
| **4** | 6.07 | 0.55 | 6.80 | 0.26 | 7.30 | 0.26 | 7.03 | 0.46 | 9.53 | 0.64 | 9.37 | 0.55 | 11.70 | 0.44 | 11.69 | 0.35 |
| **5** | 6.83 | 0.75 | 6.79 | 0.15 | 7.93 | 0.06 | 7.93 | 0.21 | 9.57 | 0.32 | 9.57 | 0.46 | 11.20 | 0.26 | 11.19 | 0.38 |
| **6** | 6.73 | 0.32 | 6.73 | 0.21 | 7.23 | 0.42 | 7.23 | 0.38 | 9.63 | 0.31 | 9.61 | 0.47 | 11.77 | 0.42 | 11.77 | 0.15 |
| **7** | 5.30 | 0.35 | 5.21 | 0.85 | 7.13 | 0.51 | 7.10 | 0.95 | 10.30 | 0.92 | 10.28 | 0.15 | 11.97 | 36.84 | 11.96 | 0.26 |
| **8** | 6.17 | 0.70 | 6.17 | 0.15 | 7.23 | 0.83 | 7.20 | 0.30 | 9.79 | 0.26 | 9.79 | 0.23 | 11.70 | 0.53 | 11.70 | 0.31 |
| **9** | 5.43 | 0.76 | 5.40 | 0.76 | 8.47 | 0.25 | 8.41 | 0.25 | 10.77 | 0.29 | 10.77 | 0.29 | 11.53 | 0.42 | 11.52 | 0.35 |
| **10** | 5.47 | 0.67 | 5.47 | 0.14 | 8.10 | 0.10 | 8.10 | 0.67 | 9.27 | 0.40 | 9.17 | 0.46 | 11.37 | 0.65 | 11.32 | 0.71 |
| **11** | 6.63 | 0.21 | 6.63 | 0.21 | 8.90 | 0.10 | 8.90 | 0.10 | 9.97 | 0.38 | 9.96 | 0.38 | 11.67 | 0.21 | 11.67 | 0.21 |
| **12** | 6.97 | 0.35 | 6.97 | 0.31 | 7.63 | 0.49 | 7.63 | 0.17 | 9.57 | 0.12 | 9.57 | 0.75 | 11.50 | 0.82 | 11.50 | 1.00 |
| **13** | 6.47 | 0.21 | 6.24 | 0.21 | 7.77 | 0.15 | 7.72 | 0.15 | 9.47 | 0.40 | 9.47 | 0.40 | 11.87 | 0.29 | 11.84 | 0.29 |
| **14** | 5.63 | 0.21 | 5.61 | 0.21 | 8.90 | 0.10 | 8.87 | 0.10 | 9.97 | 0.38 | 9.97 | 0.38 | 11.67 | 0.21 | 11.67 | 0.21 |
| **15** | 5.67 | 0.85 | 5.67 | 0.21 | 7.70 | 0.66 | 7.70 | 1.06 | 10.00 | 0.61 | 10.00 | 0.06 | 11.33 | 0.49 | 11.33 | 0.83 |
| **16** | 5.63 | 0.21 | 5.63 | 0.21 | 8.90 | 0.10 | 8.90 | 0.10 | 9.97 | 0.38 | 9.97 | 0.38 | 11.67 | 0.21 | 11.63 | 0.21 |
| **17** | 5.17 | 0.57 | 5.17 | 0.07 | 8.33 | 0.55 | 8.31 | 0.78 | 9.13 | 0.45 | 9.13 | 0.76 | 11.67 | 0.21 | 11.65 | 0.51 |
| **18** | 5.60 | 0.17 | 5.60 | 0.07 | 7.60 | 0.52 | 7.56 | 1.51 | 9.03 | 0.35 | 9.03 | 0.85 | 11.90 | 0.35 | 11.90 | 1.07 |
| **19** | 6.20 | 0.61 | 6.20 | 0.40 | 7.97 | 0.15 | 7.93 | 0.70 | 9.83 | 0.12 | 9.83 | 0.51 | 11.43 | 0.38 | 11.43 | 0.66 |
| **20** | 6.33 | 0.06 | 6.33 | 0.06 | 7.53 | 0.55 | 7.52 | 0.55 | 10.30 | 0.17 | 10.30 | 0.17 | 11.47 | 0.35 | 11.47 | 0.35 |
| **21** | 6.63 | 0.21 | 6.63 | 0.21 | 8.90 | 0.10 | 8.78 | 0.10 | 9.97 | 0.38 | 9.97 | 0.38 | 11.67 | 0.21 | 11.67 | 0.21 |
| **22** | 5.03 | 0.32 | 5.13 | 0.47 | 8.03 | 0.78 | 8.03 | 0.38 | 9.77 | 0.93 | 9.77 | 0.23 | 11.50 | 0.56 | 11.23 | 0.55 |
| **23** | 5.73 | 0.35 | 5.77 | 0.50 | 7.50 | 0.70 | 7.50 | 1.01 | 9.50 | 0.69 | 9.45 | 0.14 | 11.57 | 0.35 | 11.57 | 0.70 |
| **24** | 5.27 | 0.47 | 5.27 | 0.80 | 8.00 | 0.89 | 8.10 | 1.15 | 9.90 | 0.87 | 9.90 | 0.92 | 11.07 | 0.58 | 11.07 | 1.01 |
| **25** | 6.47 | 0.67 | 6.40 | 0.24 | 8.13 | 0.59 | 8.13 | 0.47 | 9.33 | 0.93 | 9.32 | 0.23 | 11.60 | 0.00 | 11.59 | 0.60 |
| **26** | 5.57 | 0.96 | 5.57 | 0.25 | 7.23 | 0.15 | 7.23 | 0.72 | 9.53 | 0.47 | 9.53 | 0.47 | 11.53 | 0.12 | 11.53 | 0.84 |
| **27** | 6.43 | 0.76 | 6.38 | 0.12 | 8.47 | 0.25 | 8.42 | 0.60 | 9.77 | 0.29 | 9.72 | 0.10 | 11.90 | 0.35 | 11.88 | 0.56 |
| **28** | 6.57 | 0.12 | 6.57 | 0.65 | 8.43 | 0.29 | 8.43 | 0.66 | 9.70 | 0.17 | 9.89 | 0.46 | 11.50 | 0.82 | 11.50 | 0.10 |
| **29** | 6.47 | 0.21 | 6.41 | 0.60 | 7.77 | 0.15 | 7.72 | 0.17 | 9.47 | 0.40 | 9.47 | 0.46 | 11.87 | 0.29 | 11.87 | 0.23 |
| **30** | 5.73 | 0.74 | 5.73 | 0.46 | 8.13 | 0.31 | 8.11 | 0.26 | 9.37 | 0.15 | 9.37 | 1.22 | 11.47 | 0.25 | 11.47 | 0.21 |
| **31** | 5.63 | 0.21 | 5.62 | 0.06 | 8.90 | 0.10 | 8.89 | 0.30 | 9.97 | 0.38 | 9.97 | 0.35 | 11.17 | 0.67 | 11.16 | 0.44 |
| **mean** | 6.05 | | 6.04 | | 7.97 | | 7.96 | | 9.72 | | 9.71 | | 11.58 | | 11.57 | |

### 6.4.2. Y-axis coordinate of toe-off

The results show that, for all 31 subjects moving with simulated body weight, the y-axis coordinate values increased at toe off. In all four groups (SBW and NBW), left foot and right foot values were almost the same values for each condition (0, 10, 20, and 30 kg). However, left and right foot values did show the differences for NBW (0 kg) and simulated (10, 20, and 30 kg) weights. The results for y-axis coordinate values for both feet, are given in **Table 6.6**.

For both feet, the NBW group (0 kg) was lower at the y-axis coordinate mean values than the SBW group (10, 20, 30 kg). The y-axis coordinates mean values for NBW (0 kg) and SBW of 10, 20, 30 kg for the left foot were 5.84, 8.03, 9.40, and 11.53 mm respectively. In addition, y-axis coordinate mean value of the right foot were 5.83, 8.02, 9.39, and 11.52 mm, respectively for the NBW (0 kg) and SBW of 10, 20, 30 kg.

**Table 6.6.** The mean value and SD for left and right foot in toe-off phase (y-axis coordinate, mm)

| | Toe-off- Left and right foot X-axis | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Participants** | 0kg | | | | 10kg | | | | 20kg | | | | 30kg | | | |
| **Id** | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD | Mean Lf | SD | Mean Rf | SD |
| **1** | 5.43 | 0.80 | 5.43 | 0.36 | 8.67 | 0.31 | 8.62 | 1.82 | 9.57 | 0.85 | 9.57 | 0.00 | 11.20 | 0.10 | 11.19 | 0.12 |
| **2** | 5.53 | 0.21 | 5.53 | 0.15 | 7.63 | 0.51 | 7.63 | 0.40 | 9.09 | 0.52 | 9.09 | 0.44 | 11.73 | 0.68 | 11.73 | 0.52 |
| **3** | 5.53 | 0.21 | 5.53 | 0.31 | 7.63 | 0.51 | 7.70 | 0.42 | 9.09 | 0.52 | 9.50 | 0.32 | 11.73 | 0.68 | 11.73 | 0.67 |
| **4** | 5.53 | 0.32 | 5.53 | 0.15 | 7.70 | 0.26 | 7.60 | 0.40 | 9.53 | 0.06 | 9.09 | 0.44 | 11.73 | 0.21 | 11.73 | 0.49 |
| **5** | 5.77 | 0.60 | 5.76 | 0.12 | 7.47 | 0.31 | 7.47 | 0.42 | 9.17 | 1.72 | 9.17 | 0.21 | 11.73 | 0.40 | 11.67 | 0.61 |
| **6** | 5.90 | 0.78 | 5.90 | 0.21 | 7.47 | 0.58 | 7.42 | 0.90 | 9.37 | 0.38 | 9.37 | 0.36 | 11.13 | 0.06 | 11.13 | 0.06 |
| **7** | 6.37 | 0.80 | 6.37 | 0.60 | 7.70 | 0.92 | 7.66 | 0.70 | 9.37 | 0.61 | 9.29 | 0.52 | 11.87 | 0.81 | 11.87 | 0.81 |
| **8** | 5.97 | 0.84 | 5.97 | 0.95 | 7.17 | 0.67 | 7.12 | 2.89 | 9.57 | 0.15 | 9.52 | 0.15 | 11.60 | 0.35 | 11.60 | 0.20 |
| **9** | 5.20 | 0.72 | 5.20 | 0.72 | 8.60 | 0.44 | 8.60 | 0.44 | 9.27 | 0.86 | 9.22 | 0.86 | 11.27 | 0.59 | 11.27 | 0.59 |
| **10** | 6.30 | 0.42 | 6.30 | 0.65 | 8.17 | 0.12 | 8.17 | 0.83 | 9.30 | 1.48 | 9.30 | 0.45 | 11.47 | 0.23 | 11.47 | 0.17 |
| **11** | 6.17 | 0.06 | 6.17 | 0.06 | 8.87 | 0.25 | 8.81 | 0.25 | 9.27 | 0.23 | 9.27 | 0.23 | 11.77 | 0.58 | 11.71 | 0.58 |
| **12** | 6.00 | 0.53 | 6.00 | 0.35 | 7.43 | 0.58 | 7.43 | 0.32 | 9.97 | 0.60 | 9.97 | 0.12 | 11.10 | 0.56 | 11.10 | 0.25 |
| **13** | 6.00 | 0.66 | 5.97 | 0.66 | 7.07 | 0.38 | 7.12 | 0.38 | 9.47 | 0.15 | 9.42 | 0.15 | 11.67 | 0.68 | 11.62 | 0.68 |
| **14** | 6.17 | 0.06 | 6.17 | 0.06 | 8.87 | 0.25 | 8.82 | 0.25 | 9.27 | 0.23 | 9.37 | 0.23 | 11.77 | 0.58 | 11.75 | 0.58 |
| **15** | 5.60 | 0.52 | 5.54 | 0.55 | 7.40 | 0.17 | 7.40 | 0.40 | 9.90 | 0.44 | 9.88 | 0.40 | 11.00 | 0.61 | 11.00 | 0.67 |
| **16** | 6.17 | 0.06 | 6.17 | 0.06 | 8.87 | 0.25 | 8.87 | 0.25 | 9.27 | 0.23 | 9.27 | 0.23 | 11.77 | 0.58 | 11.77 | 0.58 |
| **17** | 5.20 | 0.62 | 5.20 | 0.98 | 8.57 | 0.32 | 8.52 | 0.38 | 9.40 | 0.36 | 9.40 | 0.67 | 11.67 | 0.32 | 11.67 | 0.37 |
| **18** | 5.47 | 0.97 | 5.47 | 0.67 | 7.77 | 0.21 | 7.77 | 0.17 | 9.77 | 0.21 | 9.67 | 0.15 | 11.53 | 0.15 | 11.53 | 0.23 |
| **19** | 5.97 | 0.38 | 5.97 | 0.23 | 7.30 | 0.10 | 7.32 | 1.08 | 9.60 | 0.30 | 9.59 | 0.53 | 11.47 | 0.38 | 11.42 | 0.26 |
| **20** | 6.73 | 0.23 | 6.73 | 0.23 | 7.07 | 0.81 | 7.07 | 0.81 | 9.13 | 0.71 | 9.13 | 0.71 | 11.50 | 0.78 | 11.49 | 0.78 |
| **21** | 6.17 | 0.06 | 6.15 | 0.06 | 8.87 | 0.25 | 8.87 | 0.25 | 9.27 | 0.23 | 9.23 | 0.23 | 11.77 | 0.58 | 11.73 | 0.58 |
| **22** | 5.23 | 0.38 | 5.23 | 0.40 | 8.57 | 0.12 | 8.51 | 0.35 | 9.90 | 0.17 | 9.90 | 0.21 | 11.00 | 0.10 | 11.00 | 0.15 |
| **23** | 5.63 | 0.59 | 5.63 | 0.67 | 7.50 | 0.00 | 7.50 | 0.25 | 9.03 | 0.38 | 9.03 | 0.46 | 11.03 | 0.23 | 11.20 | 0.10 |
| **24** | 5.67 | 0.50 | 5.67 | 0.23 | 8.83 | 0.57 | 8.83 | 0.25 | 9.83 | 0.29 | 9.78 | 0.26 | 11.83 | 0.40 | 11.69 | 0.10 |
| **25** | 5.63 | 0.62 | 5.61 | 0.70 | 8.10 | 0.36 | 8.10 | 0.23 | 9.07 | 0.31 | 9.07 | 0.45 | 11.50 | 0.30 | 11.50 | 0.84 |
| **26** | 6.77 | 0.87 | 6.67 | 0.85 | 7.97 | 0.42 | 7.97 | 0.78 | 9.33 | 0.32 | 9.33 | 0.21 | 11.53 | 0.12 | 11.55 | 0.35 |
| **27** | 6.20 | 0.72 | 6.11 | 0.81 | 8.60 | 0.44 | 8.49 | 0.26 | 9.27 | 0.86 | 9.24 | 0.38 | 11.27 | 0.59 | 11.12 | 0.53 |
| **28** | 5.47 | 0.06 | 5.47 | 0.36 | 8.50 | 0.53 | 8.50 | 0.26 | 9.00 | 0.10 | 8.92 | 0.23 | 11.90 | 0.17 | 11.88 | 1.60 |
| **29** | 6.00 | 0.66 | 6.00 | 0.50 | 7.07 | 0.38 | 7.07 | 0.15 | 9.47 | 0.15 | 9.47 | 0.61 | 11.67 | 1.68 | 11.65 | 1.08 |
| **30** | 5.13 | 0.42 | 5.10 | 0.32 | 8.77 | 0.98 | 8.77 | 1.84 | 9.53 | 0.06 | 9.66 | 0.40 | 11.47 | 0.18 | 11.47 | 0.25 |
| **31** | 6.17 | 0.06 | 6.15 | 0.15 | 8.87 | 0.25 | 8.87 | 0.21 | 9.27 | 0.23 | 9.27 | 0.26 | 11.77 | 0.58 | 11.77 | 0.15 |
| **mean** | 5.84 | | 5.83 | | 8.03 | | 8.02 | | 9.40 | | 9.39 | | 11.53 | | 11.52 | |

## 6.5. Discussion

For the simulated body weight, a positive correlation was found between the increase in body weight and mean value for both x-axis and y-axis coordinates. The results of this experiment suggest that the increased weight by SBW can significantly increase x axis and y-axis coordinate mean values. So, the developed system does offer a new innovative technique for the calculation of angles and centroid of the area of contact. The results and analysis are limited to three significant stages of the load phase: 1) Heel strike, where the heel is in initial contact with the substrate. 2) Midstance or the instant in the gait cycle where the swing leg passes the support leg. 3) Toe-off or the instant before the plantar surface leaves the substrate.

Best on our knowledge, this is the first study to examine the relationship between dynamic foot alignment and centroid plantar pressure patterns in adults. The investigation used an insole system to capture the plantar surface data of 31 subjects with differing SBW. Participants were divided into three categories. Based on our best knowledge there is no research that studies simulated body weight to evaluate the x-location and y-location of the foot plantar during gait, thus, it is hard to compare these results with those of other researchers. Founded on the limited data for x-locational change, it seems that the NBW (0 kg) subjects' foot pressure compressed the soft plantar tissue more than the SBW of subjects (10, 20, 30 kg) when a load was applied.

## 6.6. Centroid of the foot plantar during gait

Changing the magnitude of the weight on the moving foot is a method that can help foot specialists to determine the cause of increased pressure of the plantar surface. In addition, the data can be used for medicine, sport and applications associated with footwear design. Thus, this research introduces a novel procedure to match increased body weight by simulation to determine the foot x-axis and y-axis coordinate values in three phases (heel strike, midstance and toe off).

### 6.6.1. Centroid of heel strike contact surface for the simulated body weight

This result indicates that increased body weight will lead to increased heel strike for both x-axis and y-axis coordinate mean values for both feet. The greater mean value for both coordinates (x-axis and y-axis) were with the 30kg, which were 12.59 and 12.18 mm for both feet.

#### 6.6.2. The centroid of midstance contact surface for the simulated body weight

This result indicates that increased body weight will lead to an increase in both x-axis and y-axis coordinate mean value for both feet in midstance phase. The larger mean value for both coordinates (x-axis and y-axis) was 30kg for both feet, which were 6.59 and 6.90 mm.

#### 6.6.3. The centroid of toe-off contact surface within the simulation body weight

This result indicates that increased body weight will lead to an increase in both x-axis and y-axis coordinate mean values for both feet. The largest mean values for both x-axis and y-axis coordinates were 30kg for both feet, which were 11.57 and 11.52 mm.

The results of the SBW indicate that a higher prevalence of overweight and obesity leads to an effect on the sole of the foot when other complicating agents, like the attendance of deformities and finite joint movability are controlled. The rationale for such an occurrence is that the soft tissue of overweight and obese subjects is constantly subjected to heavier weight thus having a small change in weight no longer had a greater impact.

As the data was normalised according to the total time taken for the loading phase of the gait, the y-locational change was due partly to the extra weight, which could increase the time of lifting the foot. Therefore, the results showed that the x-locate and y-locate change can help to calculate the change in the rotation of the ankle joint. The developed techniques could be used to demonstrate the effect of walking along hilly walkways.

## 6.7. Chapter summary

This chapter provides a better understanding of the connection between the simulated body weights and the centroid of the foot plantar during gait, and foot angles (heel strike angle and toe angle) for the loading phase of human gait. The participants were 31 males from a Southern Queensland University. They were instructed to walk freely, in a three-step gait trial on a level surface with a pressure system. Walking data was recorded by an insole capturing system.

The x and y-location means for the left and right sides were comparable and the combined values have presented the relationship between dynamic foot alignment and foot pressure patterns in participants with different loads.

The test data shows different mean x-axis and y-axis coordinate values under simulated body weight in all foot phases. The research results also show that the characteristics of the impact of body weight loading on the plantar surface varies between individuals. These conclusions allow the creation of a set of practical recommendations for future work that can be done in relation to the system. The utilisation of an innovative pre-marked medial foot reference and the advanced insole foot pressure sensor have enabled the demonstration of the effect of overweight on ankle motion. Preliminary tests show that the technique is practical for clinical studies and demonstration. Further testing will be needed to establish the suitability of the techniques for developing an indexing scheme for the study of ankle injury in obese people.

The next chapter presents a summary and final conclusion for the thesis and identifies the possibilities for further research.

# 7. CONCLUSIONS

## 7.1. Introduction

This chapter summarises the overall conclusions of this research. Detailed conclusions corresponding to the experiments and the result of each objective can be found in **chapter 4, to chapter 6**, respectively. Based on these conclusions, a set of practical recommendations is provided in **chapter 7**.

Advancing the knowledge of human foot function and bodyweight loading impact on foot performance is a crucial area of human health research. This knowledge is particularly important for the study and treatment of pathological injured and deformed feet. Therefore, a number of investigations were carried out to determine whether the continuous capture by an insole system during walking could assist in understanding the loading characteristics and structural behaviour of the foot. The study discusses the various methods and the approaches used for achieving the effects of body weight or simulation of body weight and correlation. The findings of these studies are summarised below. The study discusses the various methods and the approaches used for achieving this correlation. Three objectives were established to accomplish the research aim. These objectives were: **1)** assessing dynamic foot plantar pressure characteristics in adults, who were of normal weight, overweight and obese, during level walking using the insole pressure system, and then comparing those values (findings) with those of a healthy control group, **2)** studying the impact of simulated body weight (SBW) to increase the BMI from healthy to overweight and obese on gait measures, by comparing large simulated BMI (wearing a vest with 10, 20, and 30 kg weight) with the control group (who was tested without any weight or un-simulated body weight group, NBW), and **3)** evaluating the spatial relationship between the trace of the centroid of the area of contact with heel strike, midstance, and toe-off phases with simulated body weight (SBW) groups, using the in-shoe plantar pressure system. Below are the conclusions of the study based on each research objective.

# CHAPTER 7: CONCLUSIONS

**Objective 1**:

This objective was achieved by classifying participants into three groups (healthy, overweight and obese) according to BMI to capture plantar foot pressure. Results derived from this research show that the obese group has identified significant impact compare to the other two groups: healthy and overweight within the foot plantar pressure parameter features (F, CA, CP, PTI, and PP) within ten different foot regions. It has been noted that the highest regions of F measures were found with the obese and overweight groups under the H, 1MH, $1^{st}$T, followed by the 2MH when compared to the controls. CA was highest under the H, 1MH, MF, and 2MH areas. CP was higher beneath the 2MH, 3MH, H, $1^{st}$T, and 1MH regions. PTI was highest under the H, $1^{st}$T, 2MH, and 3MH regions. And PP was highest under the H, $1^{st}$T, and 2MH areas. The forefoot appears to be more sensitive to weight-related pressure under the foot than the rearfoot. Results also suggest that obese participants, to higher BMI, experienced increased plantar foot pressure when compared to healthy weight and overweight participants because obese participants have greater body mass. Notably, the feet of obese individuals are wider than those of healthy and overweight adults. Findings from this study indicate that being overweight or obese increases foot pressure measures even for individuals with similar body features. These findings have implications for pain and discomfort in the lower extremity in the obese, and in the predisposition to participate in activities of daily living, such as walking.

**Objective 2**:

To accomplish this objective, an additional weight was added to increase a participant's body weight (10, 20, 30 kg), to foot plantar measures. This method allows a reduction in resources, such as time for increasing or reducing participants' weights. The results derived from the SBW showed that SBW is positively correlated to foot plantar measure values compared to the NBW group. Additional weight added (SBW) to increase the participants' body weight allowing them to reach a higher BMI), indicated that there were statistically significant increases in force measure between the SBW (10, 20, 30 kg) compared with the NBW group within the H, 1MH, 2MH, and MF regions, respectively. And, for contact area, H, 1MH, and MF were three main regions that made the largest CA measures with SBW (30, 20, 10 kg). Moreover, 2MH, H, and 3MH displayed statistically significant increases in mean CP value in all SBW sessions. In addition, H, 2MH, and 3MH regions displayed statistically significant increases in mean PTI in the SBW groups compared to the NSBW group. Furthermore, a statistically significant increase in PP between the 30, 20, 10 kg and NSBW was evident in all other regions. The regions of $3^{rd}$-$5^{th}$T and $2^{nd}$T, in contracts did not display any statistically significant differences in changes with SBW compared to the NSBW group in which all five most clinically relevant parameters were obtained: F, CA, CP, PTI and PP. The values or results of CV and ICC for analysis showed a generally good level of reliability, the quality of which is dependent on the region of the foot and the variable investigated with SBW loads.

**Objective 3**:

To achieve the last objective, the centroid trace of the plantar contact area of thirty-one subjects (identification: 1 to 31) were compared the heel strike, midstance, and toe-off phases with SBW groups to the other NBW group, using the in-shoe plantar pressure system. As discussed, this objective provides an advanced understanding of the spatial relationship between the area of contact during heel strike, midstance, and toe-off phases, noting the SBW groups of human gait. This objective also provides a better understanding of the plantar soft tissue mechanics during walking. The tests showed that the technique is practical for both a clinical study and clinical demonstration. The centroid coordinates x-axis and y-axis with coordinate values have demonstrated a significant increase in simulated bodyweight groups within the three stages of the load phase: heel strike, midstance; and toe-off, for both feet. A change in the magnitude of the load on the moving foot is a method that can help foot specialists determine the cause of increased pressure on the plantar surface.

## 7.2. Overall conclusions

Overweight and obesity are growing problems throughout the world and adults suffering from these conditions are particularly at risk of suffering health issues. Furthermore, the associated comorbidities of obesity are increasingly evident.

Biomedical, physiotherapy and clinical studies show that humans can be distinguished by unique limb movement patterns and plantar pressure patterns if they are obese or non-obese. Being overweight and obese restrict mobility and physical exercise, which are essential for maintaining good health. Body weight is the main factor for increasing results in the plantar pressures foot measure. Advancing the knowledge of human foot function and body weight loading impact on foot performance has been a crucial area of research into human health. This knowledge is particularly important for the study and treatment of pathologically injured and deformed feet. The pressure system is becoming popular for capturing accurate plantar pressure data for overweight, obese and healthy adults and children.

Presently, there are few studies on the alterations in gait features of overweight and obese adults with small differences in BMI over a short time, particularly precision tracking of the lower limbs, including ankles and feet. The purpose of this study is to determine the relationship between BMI and gait characteristics with the aim of evaluating the relationship between lower limb and foot biomechanical measures and plantar pressure measures in adults aged 24 to 50. Changes in plantar pressure distribution parameters were evaluated using an insole shoe system during comfortable walking speed under simulated body weight conditions. Clinically, force, contact area, contact pressure, plantar pressure integral and peak pressure are the foot parameters that are most relied upon.

Pressure distribution measurement techniques are useful in analysing the mechanical behaviour of the human foot during dynamic loading situations in adult subjects. Hence, there is a need for a complete analysis of the variation of pressure distribution patterns under both feet while body weight is simulated through three different weights. Additionally, it is important to make and analyse a comparison of these weight pressure distribution patterns under the foot.

## 7.3. Limitations of the research

As with any experimental study, due to the operating conditions and laboratory environment, this study has some limitations, which should be acknowledged. These are:

1. Although all testing was conducted within university hours (9:00 am - 4:00 pm), results may have varied among adults due to differences in the time of day the assessments were conducted;
2. Participants were selected from the available population at university;
3. The tests were conducted in a laboratory setting which does not represent the gait environment of the real world;
4. Male participants presented at various body weights (68-142.5) kg and BMI (20.1- 46.0 kg/m$^2$);
5. The participants recruited for these studies were aged between 24 to 50 years;
6. These findings are restricted to a generalisation for adults within this age range;
7. Participants walked at self-selected speeds;
8. In-shoe techniques can only provide information about forefoot conditions. Therefore, the results cannot reveal the impact of the barefoot plantar surface;
9. Walking at speed and running were not tested during this investigation due to limitations;
10. The current study examined and provided results for males, so these conditions cannot be generalized to females;
11. Despite familiarizing the adults with each protocol, adults may have altered the way they typically performed a task because they were aware that they were being assessed;
12. Participants were wearing vests with different weights (10, 20 and 30kg) which was a limitation that could have influenced the gait parameters while walking;
13. Limited analyses of the GRF and PP were available for the determination of stress and strain on the foot.

## 7.4. Future research

The topics of this study may open doors for new and further investigations. As an extension of this research, investigations could include the determination of the plantar surface tendency at different walking speeds and the development of effective methods of monitoring a large sample of the diabetic population in both urban and rural communities. The investigation might supply vital information about the characteristics of the underlying plantar muscles for high surface loading.

Further work could also include developing a comprehensive human plantar evaluation system utilising plantar 3D ultrasound data photorealistic textured 3D plantar surface and plantar surface pressure data of the dynamic foot during gait. Photographic examination may reveal attributes of the foot that could cause increased loading of the plantar soft tissue and skin breakdown.

Further research is required to investigate the relationship between obesity and foot structure during different walking speeds. In future studies, we will investigate a larger number of subjects and will also consider foot arch height and postural sway of all subjects to understand plantar pressure distribution variations on both feet due to external perturbation. Moreover, this would provide a direct measure of soft tissue features such as plantar fascia length, elongation/strain, and 3D shape changes and, as a consequence, would enable direct assessment of in vivo mechanical properties.  It is necessary to examine factors that may influence the function of the quadriceps and walking speed and to longitudinally evaluate the influence of the foot.

The following recommendations for further study depend on the results of the current study suggesting that overweight and obesity have a negative effect on adults. Whether the increased pressures are associated with foot discomfort to prevent an obese adult from participating in physical activity requires further investigation. In addition, further investigation of the effects of obesity on the musculoskeletal structure and biomechanical function of young adults is also suggested. Encouraging overweight and obese individuals to lose weight even by a modest amount, is important to improve their healthy status. The decrease in body weight can significantly reduce the risk of developing neuropathic foot ulcers through the reduction of pressure. Noticeably, this association can play a significant role in the diabetic population.

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# APPENDICES

## [Appendices A - Human Research Ethics Committee]

**OFFICE OF RESEARCH**
Human Research Ethics Committee
PHONE +61 7 4631 2690| FAX +61 7 4631 5555
EMAIL human.ethics@usq.edu.au

UNIVERSITY OF SOUTHERN QUEENSLAND

3 May 2018

Miss Suhad Kareem Rahi Al-Magsoosi
Darling Heights
4350

Dear Suhad

The USQ Human Research Ethics Committee has recently reviewed your responses to the conditions placed upon the ethical approval for the project outlined below. Your proposal is now deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* and full ethical approval has been granted.

| | |
|---|---|
| Approval No. | H18REA065 |
| Project Title | BMI variation and its effect on gait in overweight and obese adults |
| Approval date | 3 May 2018 |
| Expiry date | 3 May 2021 |
| Status | **Approved with standard conditions** |

The standard conditions of this approval are:

(a) responsibly conduct the project strictly in accordance with the proposal submitted and granted ethics approval, including any amendments made to the proposal;
(b) advise the University (email: ResearchIntegrity@usq.edu.au) immediately of any complaint pertaining to the conduct of the research or any other issues in relation to the project which may warrant review of the ethical approval of the project;
(c) promptly report any adverse events or unexpected outcomes to the University (email: ResearchIntegrity@usq.edu.au) and take prompt action to deal with any unexpected risks;
(d) make submission for any amendments to the project and obtain approval prior to implementing such changes;
(e) provide a progress 'milestone report' when requested and at least for every year of approval;
(f) provide a final 'milestone report' when the project is complete;
(g) promptly advise the University if the project has been discontinued, using a final 'milestone report'.

For (d) to (g) forms are available on the USQ ethics website:
https://www.usq.edu.au/current-students/academic/higher-degree-by-research-students/conducting-research/human-ethics/forms-resources

Please note that failure to comply with the conditions of approval and the *National Statement (2007)*, may result in withdrawal of approval for the project.

Yours sincerely,

**Mrs Nikita Kok**
Ethics Officer

# APPENDICES

## [Appendices B - Consent Form]

The University of Southern Queensland

Consent Form

To: Participants

Full Project Title: BMI variation and its effect on gait in overweight and obese adults.

Principal Researcher: Dr. Albert Chong

Student Researcher: Miss Suhad Kareem Rahi Al-Magsoosi

ID: H18REA065

I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.

•□I understand the purpose of the research project and my involvement in it.

•□I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.

•□I confirm that I am over 18 years of age.

•□I understand that while information gained during the study may be published, I will not be identified, and my personal results will remain confidential.

•□I understand that the video footage recorded of my foot during the research will be stored in a password protected computer at the University of Southern

Queensland and access will only be granted to the researchers involved in the study.

•□ I understand that only my lower limbs (knee and foot) will be videotaped during the study.

Name of

Participant………………………………… Phone…

Signed……………………………………………………. Date………………………

If you have any ethical concerns with the research

OFFICE OF RESEARCH

Human Research Ethics Committee

PHONE +61 7 4631 2690| FAX +61 7 4631 5555

EMAIL human.ethics@usq.edu.au

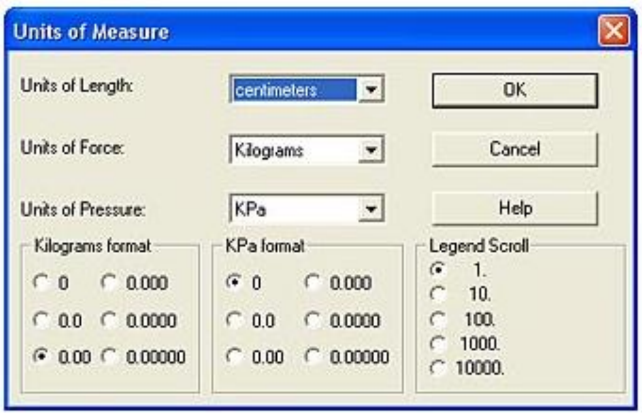
# [Appendices C - The calibration procedure]

### Performing a step calibration for a known weight:

The following procedure is used to perform a step calibration on the left and right ***F-Scan*** sensors. This procedure must be performed on each foot separately. The process below will calibrate the left foot first, and then the right.

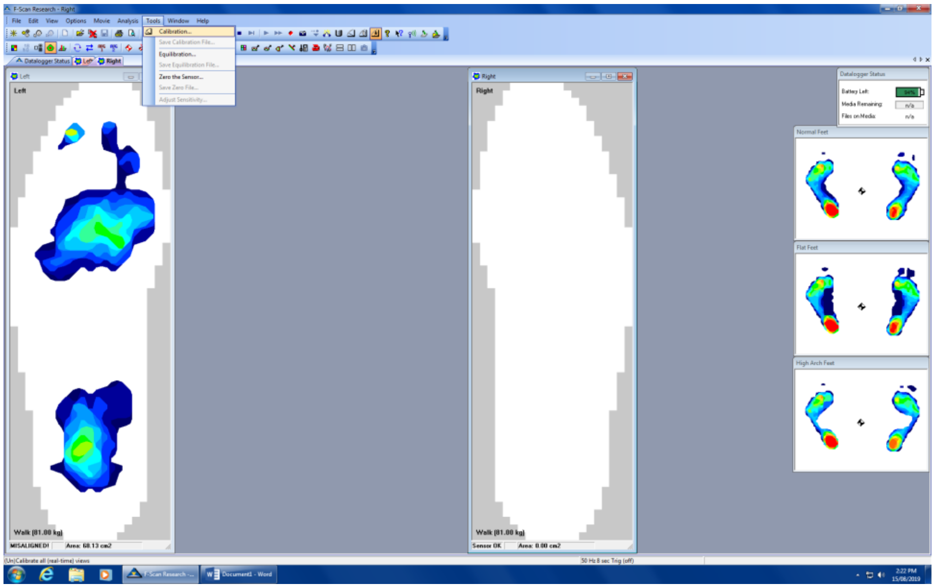
1. Refer to the "Preparing the Patient" section, and get the subject ready for testing. Open a pair of new Real-time windows for the subject.

2. Select the force and pressure units to be use in the calibration. The default units are "pounds (force)" and "PSI (pressure)". If other units are required, select **Measurement Units** from the "Options" menu, and make the changes (see image below).

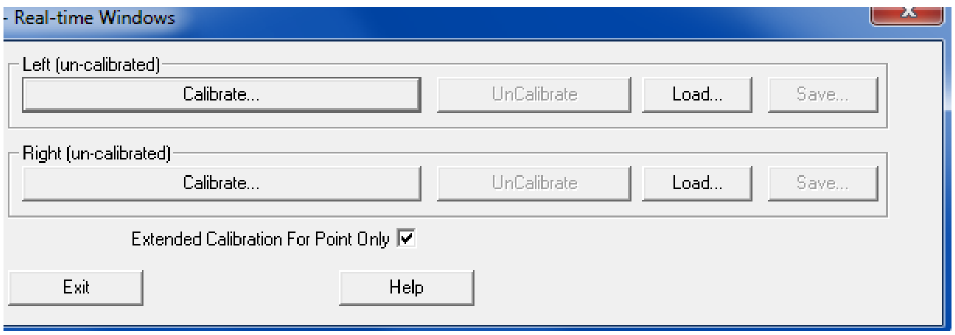



3. Insert the participant weight:

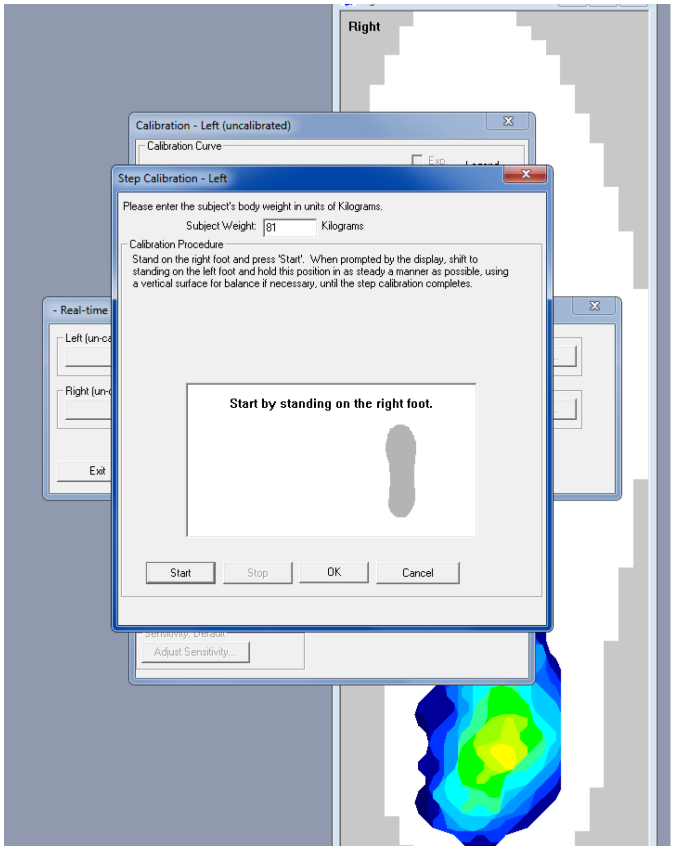

4. Tools were clicked on the taskbar calibration was selected.



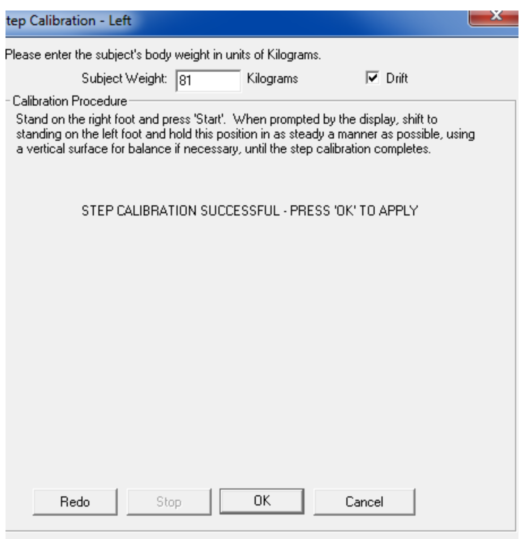
5. We are first going to calibrate the left foot. With the left real-time window highlighted (the title bar will be blue), click the "Step Calibration" icon on the toolbar.

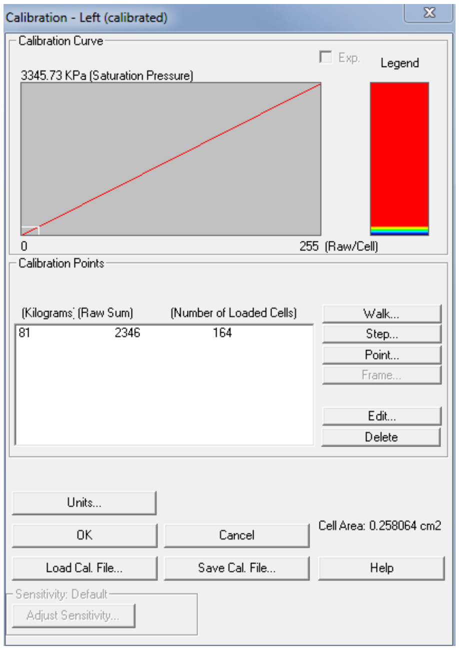



6. The "Step Calibration" dialog opens (shown below right) with instructions on how to proceed. Enter the subject's weight in the "Subject Weight" field (shown below Left).

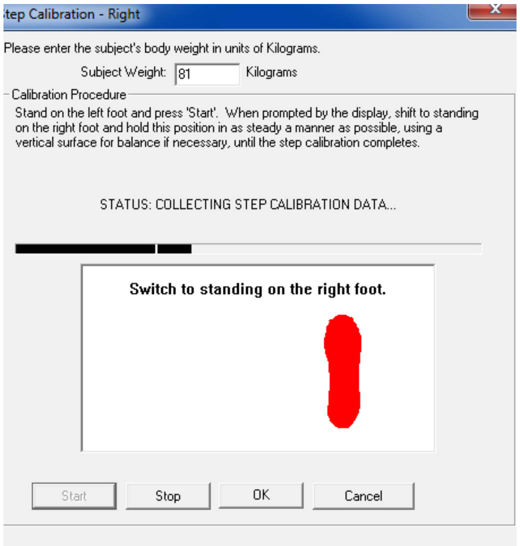



7. If the calibration is correctly performed, the following "Step Calibration" screen is displayed, showing a successful calibration. Click the **OK** button to accept the calibration for the left foot.



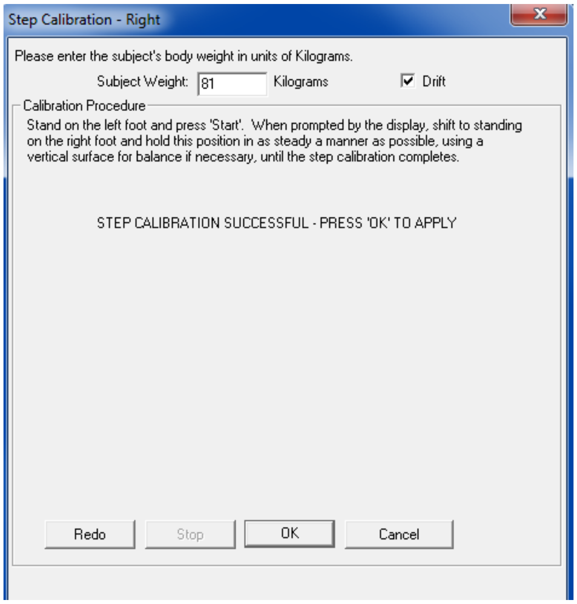



5. Have the participant stand on their right foot (the foot to be off-loaded). Click the **Start** button. A timer bar starts to count down the calibration process. Notice the white bar located about 1/4 the way along this timer bar. This is the point at which the subject must switch feet and stand entirely on their left foot.




6. When the white vertical bar on the timer is reached, have the patient switch feet and stand entirely on their left foot. This will occur rapidly, so care must be taken to have the subject switch at the correct moment. It is important that the subject's weight be entirely borne through the foot being calibrated (here the left foot).

7. If the calibration is correctly performed, the following "Step Calibration" screen is displayed, showing a successful calibration. Click the **OK** button to accept the calibration for the left foot




8. If an error occurs during the calibration process, or the incorrect foot is used during calibration, the following error messages are presented on-screen. The foot calibration will have to be redone


If the calibration is correctly performed, the following "Step Calibration" screen is displayed, showing a successful calibration. Click the **OK** button to accept the calibration for the left and right foot.