# AN INNOVATIVE STATISTICAL METHODOLOGY TO IMPROVE HUMAN GAIT ANALYSIS

A Thesis submitted by

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# Abstract

Human locomotion through the movement of limbs is called human gait. Accordingly, examining this human locomotion is named human gait analysis. As human locomotion is related to many aspects and applications in our lives, human gait analysis has become an attractive and important subject to researchers and specialists from various disciplines. The most crucial applications of human gait analysis are in the clinical sectors. It is, for example, used to gain a better understanding of the normal and pathological gait, which helps to: 1) reach better diagnoses and 2) deliver better treatments.

In general, studying human gait involves recording trials of participants (e.g. walking), and then extracting and analysing the resulted data. Trials are commonly conducted by recruiting a large number of participants to perform a small number of trials. Conducting such trials is time consuming, resource intensive and costly. In addition, it is sometimes difficult to find a sufficiently large number of participants to examine the gait of particular types of patients who have conditions affecting their ability to walk normally. As a result, there is a need for a more efficient approach to conducting human gait analysis.

This research aims to introduce an innovative alternative statistical methodology to improve the conduct of human gait analysis. It can be considered a better approach to the currently available approaches because it: 1) requires less effort, cost and time, and 2) gives more reliable results.

The main phases of the proposed approach are collecting very accurate data from a small number of participants, combining this data with published data, and calculating the final results from the combined data. To establish such a methodology, new protocols and techniques are needed to collect more accurate data and combine data from several sources. For the first purpose, data from a small number of participants in a big number of trials were collected. The pressure measuring system used in this research was 300E F-Scan insole-sensors. In addition, one-step and three-steps-mean protocols were used in the data collection. For the second purpose, statistical techniques were used to combine data from self-captured trials and published works by assigning weights (using variance, coefficient of variation, etc) for each measurement, and to calculate the final results (i.e. weighted mean and standard error) of the combined data.

Therefore, using the proposed innovative alternative statistical methodology to conduct human gait analysis involves: 1) collecting data from published articles, 2) collecting more accurate data (matching to the published data) from self-captured trials by using the one-step and three-steps-mean protocols, 3) determining the better protocol by comparing their results, 4) combining the published data with those of the better protocol, and 5) computing the final results from the combined data.

Three studies were conducted to analyse some parameters of human using the new methodology. Each study involved five participants of particular conditions. The three groups of participants were: healthy young adults, healthy older adults and obese adults. Each participant was asked to walk at a self-selected speed along a 10m walkway in a laboratory basement at the University of Southern Queensland. Participants were wearing appropriate sized shoes with 300E F-Scan insole-sensors sandwiched between the foot and the inside shoe. To eliminate the effect of acceleration and deceleration of the body at the beginning and ending of the walking trials, the middle 6-m was designated for the process of data collection. Particularly, data of the sixth, seventh and eighth steps were analysed. Every participant completed an average of 12 trials (walks), and the whole session was repeated for a second time after one week. To satisfy the independence assumption of statistical analysis, data from only one foot was analysed. In addition, data for each group were collected from published articles. Several parameters of the pressure beneath the foot from various foot regions were examined in each study.

For all three studies, the proposed protocols and alternative statistical methodology produced more accurate results. The normality of all three studies' data were checked using Shapiro-Wilks test.

For all of the three groups, data were plausibly normally distributed and most of the parameters contained no outliers. Three-steps-mean protocol gave more accurate results than those of the protocols commonly used, with the results of more than 90% of the parameters were more accurate in each study by comparing SD's. In addition, the proposed innovative statistical methodology led to better results in both cases: combining with single and multiple publications. The results showed greater accuracy for all the parameters (100%) in all cases for all of the three groups by comparing SE's with SD's.

To sum up, this research introduces a novel approach that can help experts to conduct human gait analysis more efficiently. As a result, it supports an improved understanding of human gait and, subsequently, more accurate diagnoses and effective treatments for those who can not walk normally.

# Certification of Thesis

This Thesis is entirely the work of **Kadhem Al-Daffaie** except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal Supervisor: Dr Albert K. Chong

Associate Supervisor: Dr Zahra Gharineiat

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

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# Associated Publications

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# Contents

# List of Figures

# List of Tables

# Acronyms & Abbreviations

| | |
|---|---|
| EMG | Electromyography |
| R | Reliability |
| $\sigma_t^2$ | True Score Variance |
| $\sigma_e^2$ | Error Variance |
| ICC | Intra-class Correlation Coefficients |
| MS | Mean Square |
| BMS | Between Subjects Mean Square |
| WMS | Within Subjects Mean Square |
| RMS | Between Raters Mean Square |
| EMS | Mean Square Error |
| CV | Coefficient of Variation |
| SD | Standard Deviation |
| $\bar{x}$ | Mean |
| SEM | Standard Error of Measurement |
| CR | Repeatability Coefficient |
| RF | Rearfoot |
| MF | Midfoot |
| FF | Forefoot |
| TO | Toes |
| CA | Contact Area |

| | |
|---|---|
| PP | Peak Pressure |
| PTI | Pressure Time Integral |
| MF | Maximum Force |
| MeF | Mean Force |
| FTI | Force Time Integral |
| Mea | Mean Area |
| $\sigma$ | Standard Deviation |
| $\sigma^2$ | Variance |
| w | Weight |
| M | Weighted Mean |
| SE | Standard Error |
| BMI | Body Mass Index |
| $cm^2$ | Square Centimetre |
| N | Newton Unit |
| kPa | Kilopascal |
| s | Second |
| kg | Kilogram |

# Chapter 1

# Introduction

This chapter provides a general overview of the research topic. It presents the research gap, and objectives, questions, significance and scope of the research. It also outlines the structure of the thesis.

## 1.1 Overview

Due to its importance and useful applications, human gait analysis has drawn the attention of many researchers and experts from several fields these days. Specialists use human gait analysis for different purposes in varying fields, such as sports, medicine allied health and security (Akhtaruzzaman et al. 2016).

Human gait refers to the manner of human locomotion achieved by moving limbs, including walking, running and jumping. Therefore, human gait analysis is the systematic study of human locomotion. According to Winter (2009), it is part of the so-called biomechanics of human movement, which is considered to be an interdiscipline that describes, analyses and assesses human movement. Winter (2009) also stated that experts from various disciplines, such as doctors, therapists, rehabilitation engineers and athletes, work in this scientific area due to its valuable applications.

Studying human gait requires the use of the eyes and brain of experienced observers, enhanced by some devices and tools that measure several parameters related to human body parts and muscles that cause movements (Levine et al. 2012). Experts have been using various techniques and devices such as video recordings, pressure measuring systems and electrodes to record different types of gait data. Tao et al. (2012), Muro-De-La-Herran et al. (2014) and Abdul Razak et al. (2012) pointed out that the techniques used for capturing gait data vary depending on the devices utilised. They stated that these techniques are based on image processing, floor sensors or sensors located on the body.

Improvements to such devices and tools have delivered more efficient ways of gathering more reliable information on human gait (Muro-De-La-Herran et al. 2014). This has helped bring human gait analysis to an advanced point where it is now a part of routine assessments of human movement for several purposes (Whittle 1996).

To examine and evaluate human gait, data of several characteristics and measurements must be studied. These characteristics can be classified into three general categories: kinematics, kinetics and electromyography (EMG). Kinematics analysis deals with the measurement of movement, where data represent the position and motion of any point of the subject to describe the locomotion pattern without considering force (Akhtaruzzaman et al., 2016). Kinetic data deal with the force resulting from the interaction between the foot and the contact surface (Whittle 1996). Data from electromyography (EMG) take into consideration the measurements of muscle action in the lower extremity in human gait (Tao et al. 2012).

There are several benefits of gait analysis:

(i) **In medical sectors**

As problems in human walking can lead to serious health issues, understanding human gait helps specialists make more comprehensive diagnoses and provide more effective treatments for those who have ailments affecting their ability to walk normally. It can be used to deliver better care to patients (Davis 1997). According to Whittle (1996), in addition, human gait analysis has been considered as a very useful tool for physicians and therapists. It also has been used by clinicians for rehabilitation purposes, where they can evaluate gait conditions of patients and then make appropriate treatment decisions (Baker 2006). Once treatment has commenced, they can also use human gait analysis to monitor patient progress and even predict subsequent treatment outcomes. Similarly, experts have employed such analysis to choose suitable orthoses for patients with abnormal walking conditions or to evaluate the efficiency of these devices (Brehm et al. (2008) and Romkes & Brunner (2002)). Other researchers have used human gait variables along with classification techniques to categorise patients into certain groups, which is critical to the diagnosis of neuromuscular disorders (Yousefi & Hamilton-Wright 2014) or the prediction of falling behaviour (Begg & Kamruzzaman 2005).

(ii) **In security sectors**

Human gait analysis has been employed to identify and recognise people at a distance (Goffredo et al. 2010), (Kale et al. 2003) and (Lee & Grimson 2002). One of the essential applications of people recognition using human gait analysis is for security purposes, where it can be used along with other techniques to detect criminals (Cunado et al. 2003).

(iii) **In sports**

Athletes and other sports professionals can also benefit from gait analysis by monitoring the manner of running or other activities. That can lead to the detection of abnormalities and then increase athletic performances and reduce injury risks (Harris & Wertsch 1994).

(iv) **In footwear industry**

The footwear industry may also benefit from studies of human gait characteristics. According to Keenan et al. (2011), findings and results from such studies should be considered in future recommendations and designs of footwear.

It is well established that experts from any discipline need to follow the scientific approach when it comes to providing a solution for a particular problem or answering a specific question. Those who work in the field of human gait also need to follow the scientific approach to perform human gait analysis. They should conduct qualitative and quantitative assessments. Winter (2009) stated that three steps are generally required to quantitatively evaluate any human movement: measuring, describing and analysing. As a result, statistical tools and methods are necessary for quantitative assessments in general and in the above mentioned three steps. For instance, professionals might need statistical tools in the measurement processes to formalise and prepare data that are suitable for analysing. Furthermore, these tools will be then utilised to describe and summarise the data. Finally, they are essential to analyse the data and gather results that are appropriate for interpretation.

Therefore, this research project has an essential interest in the statistical techniques used in human gait analysis. It introduces an innovative statistical methodology to analysis and examine characteristics and parameters of human gait. Moreover, parameters of pressure beneath the foot is of particular interest of this research. Examining such parameters has an important role in the medical applications of human gait analysis (Hessert et al. 2005). It was pointed out in that article that understanding foot pressure measurements helps to diagnose and treat some gait disorders and abnormalities.

The rest of this chapter is organised as follows: Section 1.2 presents the gap in the literature that this research tries to fill, Section 1.3 introduces the research's general aim and objectives and Section 1.4 states the research questions. The significance of this research is presented in Section 1.5. The scope of of the research is offered in Section 1.6. The last section of this chapter, Section 1.7, highlights the structure of the thesis.

## 1.2 Research Gap

From a review of the literature, detailed in the second chapter, it can be seen that the most common way of analysing human gait characteristics and conditions is to recruit suitable subjects to take part in a number of trials and then analyse the obtained data. Usually, the number of participants is large, while the number of trials is small. However, this methodology has a number of disadvantages. It requires substantial effort, time and money to: 1) find and inspire that number of people to participate in the study, 2) conduct the experiments and 3) analyse the data. In addition, it is well known that it is not easy to find a large number of participants if the study deals with particular types of patients suffering conditions such as diabetes, obesity, etc.

The existing literature has not reported any works that:

(a) Recruit a small number of participants to perform a large number of trials.

(b) Take advantage of published gait data by combining them with self-captured data to achieve more accurate results.

These strategies can help to reduce the cost, efforts and time required to recruit people, capture data, calculate measurements and analyse results. Such methods may also improve human gait analysis by achieving more accurate results.

Therefore, the research gaps in the field of human gait analysis are:

(i) A protocol to collect more accurate human gait data by using a large number of trials from a small number of participants.

(ii) An innovative statistical methodology that benefits from the use of published data along with very accurate self-captured data by combining them to achieve more accurate results for human gait studies.

## 1.3 Research Objectives

The main aim of this study is to introduce a more efficient way to conduct human gait analysis. To achieve this aim, three objectives were formalised:

1. **New protocols to capture more accurate human gait data**
   Introducing new protocols to manage human gait trials, which leads to the collection of more accurate data. These protocols are based on the idea of using a small number of participants while conducting a large number of trials.

2. **An innovative alternative statistical methodology to obtain more accurate results**
   Demonstrating an innovative alternative statistical methodology to conduct human gait analysis by combining published data with more accurate self-captured data, which might help to obtain more accurate results.

3. **Establishing the effectiveness of the innovative methodology**
   The quality of the innovative statistical methodology can be approved by:

   (a) Analysing various human gait parameters from several foot regions of three different groups of participants, i.e. healthy young adults, healthy older adults and obese adults.

(b) Combining data from self-captured trials and published works in two cases: 1) single publication and 2) multiple publications.

(c) Assessing the repeatability and identifying range values of some pressure and force parameters by using the proposed methodology.

(d) Comparing the results of the innovative methodology with those of the most commonly used methods in published works.

## 1.4 Research Questions

This research focuses on addressing the following questions:

1. **What are the technical processes for conducting human gait analysis in a more efficient way?**
   This includes:
   (a) How to preform human gait experiments by recruiting a small number of subjects to perform a large number of trials?
   (b) What types of devices could be used to conduct such experiments?
   (c) Which steps from each trial should be utilised to collect data?
2. **How to utilise statistical techniques to combine gait data from different sources, namely self-acquired and published data?**
   Which leads to the following sub-questions:
   (a) What are the sources of published data?
   (b) Which statistical technique are to be utilised to assign weights to data from several sources?

(c) Which statistical measures are useful for calculating the final results from such weighted data?

3. **What are the health conditions of the recruited participants?**

4. **How to use the new protocols and innovative statistical methodology to analysis gait data of healthy young adults, healthy older adults and obese adults?**

5. **Does using the proposed alternative statistical methodology to conduct human gait analysis lead to better results than the commonly used techniques?**

6. **What are the benefits of using the proposed methodology in the field of gait analysis?**

## 1.5 Research Significance

The most significant aspect of this research is the introduction of an improved methodology to conduct human gait analysis. This methodology provides more accurate results and requires less money, effort and time to collect and analyse gait data. Thus, it helps improve human gait analysis. The importance of this research can be described in two main points. First, this research will help to demonstrate the usefulness of one-step and three-steps-mean protocols over a large number of trials using a small number of subjects. Second, the research illustrates a method to weight and combine published and more accurate self-captured data to improve the analysis and understanding of normal and atypical human gait. By doing so, it improves the sample size and experimental results taken from a larger sample size.

As a result, the proposed methodology is useful for:

1. Experts and researchers who are interested in clinical applications of human gait analysis
2. Patients who have abnormalities in their gait
3. Athletes and coaches who can use them to improve performances.

Thus, the innovative methodology helps to provide more accurate human gait analysis, which can be used for further purposes such as:

(a) Establishing more accurate range values of any human gait parameter.

(b) Establishing more accurate results to evaluate a rehabilitation treatment or device, or any other treatment of any abnormal gait conditions.

## 1.6 Research Scope

The main scope of this research is to analyse human gait data by using an innovative statistical methodology to achieve more accurate results for the human gait analysis. This statistical methodology enables experts to combine published data and more accurate self-captured data. Another focus of this research is the use of new protocols to conduct gait trials. Data from pressure beneath the foot is of special interest in this research. Moreover, applications of human gait analysis in the medical sector is targeted.

## 1.7 Structure of the Thesis

Seven chapters are included in this thesis. They aim to introduce a proposed alternative statistical methodology to conduct human gait analysis, and use it to analyse some gait parameters of three different groups of participants. The following summarises each chapter:

The first chapter introduces a general background, and presents the research gap, objectives and questions. It also contains the significance and scope of the research.

More details about several related aspects are included in the second chapter. It provides an overview of human gait analysis, and highlights its importance in three sectors. This chapter also provides a general background of the pressure beneath the foot and two of the most common systems used to measure such parameters. In addition, it contains a critical review of the protocols used to conduct human gait trials. The reliability, statistical tools used to evaluate human gait analysis and the ways of conducting the reliability examination in gait analysis are explored in this chapter.

The third chapter includes the methodology and related aspects. The main parts of this chapter are data collecting and data analysing. The data collecting section covers the materials used in this research and the ways of gathering data from several sources. The second section covers the methods used to analyse data in this research. It discusses weighting techniques and combining data from various sources. This chapter also includes the sampling strategy and workflow of this research.

The fourth, fifth and sixth chapters discuss the procedures used in the proposed methodology to analyse some human gait parameters of three different groups of participants. They also present the results, discussions and conclusions of these three studies. The three groups of participants studied in these chapters are healthy young adults, healthy older adults and obese adults which are covered by the fourth, fifth and sixth chapters, respectively.

The last chapter presents the main findings of the thesis and highlights some possible future works.

# Chapter 2

# Background and Literature Review

This chapter provides background and a literature review of human gait analysis and some of its applications. It then focuses on pressure beneath the foot by highlighting two pressure measuring systems and critically reviewing the protocols that used in the last 10 years for collecting human pressure data. The chapter also explores the concept of reliability and some of the statistical methods used to examine it in the field of human gait analysis.

## 2.1 Human Gait: Overview

Human gait is the manner of human locomotion, especially walking, running and jumping. Tao et al. (2012) stated that the periodic movement of the human body segments is called human walking, which includes repetitive motions. Human walking can also be defined as a series of gait cycles. Thus, it is necessary to have a basic understanding of the human gait cycle before considering in human gait analysis and its importance and role in human life.

Gait cycle or stride is the period from the first contact to the ground of one foot (reference foot) until the same foot contacts the ground again (Levine et al. 2012). Each gait cycle has two phases (Perry et al. (2010) and Kirtley (2006)):

1. **Stance phase:**
   In which the reference foot is in contact with the ground. This phase has five events: initial contact, loading response, mid-stance, terminal stance and pre-swing.

2. **Swing phase:**
   In which the reference foot is moving forward through the air and has no contact with the ground. This phase contains three parts: initial swing, mid-swing and terminal swing.

Figure 2.1 shows the phases and sub-phases of each gait cycle in detail.

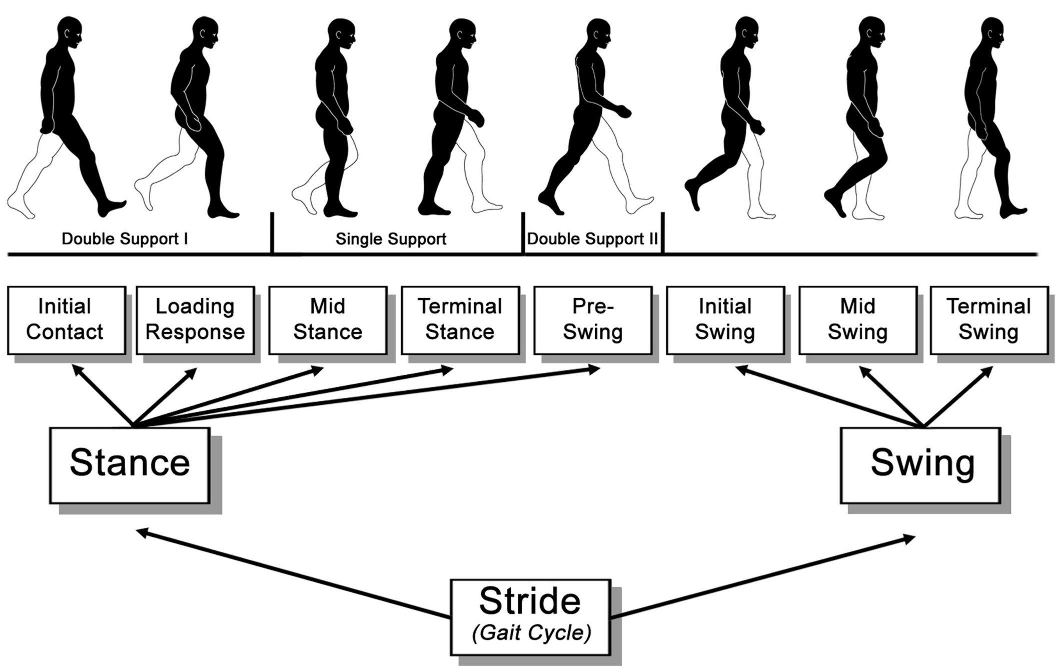


Figure 2.1: Gait Cycle (Stöckel et al. 2015)

A person's gait can be affected by a number of factors: age, gender, wearable devices, health conditions, muscle status, asymmetries of the lower extremities, injuries and pain. Levine et al. (2012) indicated that abnormal gait patterns could be caused by some health issues associated with the locomotor system. In addition, any disorders in any part of this system may produce an abnormality in the human gait. Such disorders include those in the brain, spinal cord, nerves, muscles, joints and skeleton. Moreover, (Perry et al. 2010) revealed that abnormalities in human gait can fall into five functional categories: pain, weakness in the muscle system, sensory loss, deformity and damaged motor control.

Human gait analysis has become of special interest for many experts and researchers due to its significant role in various fields. Specialists have developed and used several devices and techniques to study numerous parameters of human gait. These parameters/characteristics generally fall into three categories: kinematics, kinetics and electromyography (EMG). When conducting human gait analysis, investigators choose which type of parameters to examine depending on the purpose of their studies.

The remainder of this chapter is organised as follows: Section 2.1.1 provides a brief overview of human gait analysis. It also demonstrates the importance of human gait analysis, particularly when it is used for clinical, security and sports purposes. Section 2.3 presents a specific part of the human gait analysis which is the pressure beneath the foot. It gives a general background, displays some systems used to measure the parameters of the pressure beneath the foot and critically reviews the common protocols used in the literature to capture data of the pressure beneath the foot. Section 2.4 considers the concept of the reliability in general and the statistical techniques used to examine it. Finally, Section 2.5 explores the reliability in the context of human gait analysis.

### 2.1.1 Human Gait Analysis

Three major groups of parameters should be taken into consideration when examining the human gait (Tao et al. 2012). The first group is the kinematics. According to Winter (2009), kinematics focuses on the study of the body's movements without considering the forces (internal and external) that cause the movement. It also can be defined as the study of body segments and joints during movement in terms of their positions, angles, velocities and accelerations. The second group of parameters is called the kinetics. Kinetics refers to the examination of the forces that cause any body movements (Tao et al. 2012). To study and analyse muscle activity during human locomotion, the EMG of the human gait is used (Tao et al. 2012).

## 2.2 Importance of Human Gait Analysis

The importance of human gait analysis comes from the fact that one of the reasons behind easier, happier and healthier life is having appropriate gait performance (Akhtaruzzaman et al. 2016). That is due to the fact that typical gait will lead to normal locomotion. Some of the applications and uses of human gait analysis in our lives are shown in the following sections.

### 2.2.1 For clinical purposes

As stated earlier, the evaluation of some aspects of quality of life can be achieved by examining their gait. According to Muro-De-La-Herran et al. (2014), gait analysis becomes of particular interest considering some special health situations and diseases that negatively impact a person's ability to walk normally. For instance some neurological and systemic diseases, or those caused by aging. From a clinical point of view, knowing and monitoring the gait characteristics of patients can help specialists to diagnose some diseases earlier and recommend better treatments.

Begg & Kamruzzaman (2005) used some gait characteristics with some machine learning techniques to predict falling behavior in the elderly community. Depending on the gaits of 12 young and 12 elderly participants, they found that some gait parameters showed greater associations with fall prediction. Thus, they concluded that injurious could be prevented by early identification of changes in gait.

Brehm et al. (2008) employed gait analysis to examine the effect of the so-called ankle-foot orthoses on walking efficiency in a heterogeneous group of children with cerebral palsy. They analysed data of 172 children with spastic cerebral palsy (hemiplegia: 21, diplegia: 97 and quadriplegia: 54). By analysing and studying some gait parameters, the researchers concluded that the energy cost of walking of the quadriplegic children with cerebral palsy was decreased because of the use of an ankle-foot orthosis. On the other hand, the energy cost of walking was not affected in diplegic and hemiplegic children with cerebral palsy. Another study showed the importance of gait analysis in the field of rehabilitation is Romkes & Brunner (2002). The effect of two orthoses on gait in 12 hemiplegic cerebral palsy patients was examined. The tools of gait analysis helped the researchers to reveal that the hinged-foot orthosis resulted in significant gait improvement, while the dynamic-foot orthosis did not.

Kimmeskamp & Hennig (2001) examined some parameters of the pressure beneath the foot of 24 patients with Parkinson's diseases. They wanted to determine characteristics of the heel to toe motion of these patients. They found that these patients have a characteristic heel to toe motion pattern. It was also stated that the determination of such pattern can be useful for diagnostic, treatment and rehabilitation purposes.

### 2.2.2 For security purposes

Gait is considered to be a reliable tool for the purposes of recognising people at distance, which is very helpful in the security field. According to Fathima & Banu (2012), recognising people by gait refers to identifying them by their style of walking. In this case, a person's gait is used as a biometric measure (Lee & Grimson 2002). According to (Cunado et al. 2003), a biometric means a measure obtained from a person to be used as a recognition or identification tool such as fingerprint, face, iris, voice etc. Gait is a more valuable biometric than the others according to the fact that biometrics such as iris and face details are not easily recognised by surveillance applications at low resolution (Kale et al. 2003). Gait, howerver, can be easily detected and measured by low resolution surveillance applications (Lee & Grimson 2002).

As a result, researchers have benefited from its parameters for security purposes. For instance, Zhang et al. (2004) used gait features, namely ankle elevation, knee elevation, ankle stride width and knee stride width, along with a locomotion human model to propose a novel recognition approach. Yoo et al. (2005) described an automated system to classify gender by using general (temporal and spatial) parameters, kinematic parameters and moments.

### 2.2.3 For sports purposes

Another important use of gait analysis is for sports purposes. Athletic performance can be improved and injures can be prevented with the use of gait analysis (Wahab & Bakar 2011). It has been applied in sports, such as golf, running and basketball training (Tao et al. 2012). According to Akhtaruzzaman et al. (2016), examining the running gait of an athlete whether it has a natural or any kind of abnormal running pattern might be conducted by employing human gait analysis techniques. Monitoring that pattern and trying to improve it, in the case of having any abnormalities, will lead to better performance and lower injury possibilities.

Watanabe & Hokari (2006) used gait analysis, particularly the kinematical analysis, to introduce a method that helps to make useful measurements to evaluate sports-skills quantitatively.

Di Stasi et al. (2013) studied the differences between the gait characteristics of two groups of athletes, namely those who passed and those who did not pass the criteria of return-to-sport (RTS) six months after anterior cruciate ligament (ACL) reconstruction. They found that there are some differences between the two groups. In addition, they observed that those who did not pass the criteria of RTS had more abnormal and asymmetrical gait behaviours. These findings enable clinicians to have a testing criteria to recognise athletes with such abnormalities after ACL construction. They may also improve the sports medicine specialist's ability to identify athletes with a higher risk of secondary injury.

### 2.2.4 For footwear design purposes

Researchers have also employed it to evaluate the impacts of different types of footwear on the health of lower limbs. This application is of particular interest to specialists when recommending a specific kind of footwear for patients.

Kerrigan et al. (1998) and Kerrigan et al. (2001) studied the effects of high heeled shoes on some of the kinetics measures. Shakoor & Block (2006) found that modern shoes could negatively impact abnormalities in the lower limbs of subjects with knee osteoarthritis. As footwear plays an important role in correcting pathological gait and providing good foot support, the performance of some footwear has been studied regarding gait characteristics (Cheung & Zhang 2006). In addition, Csapo et al. (2010) illustrated the importance of using suitable footwear in gaining good foot health.

## 2.3 Pressure beneath the foot

During any human locomotion activities, the feet are the first part of the body to interact with the ground or any other surface. This means that early diagnosis of any medical issue associated with the feet could help to prevent injuries and maintain general wellbeing. According to Abdul Razak et al. (2012), one of the popular approach used to measure foot health is evaluating foot plantar pressure characteristics.

Studying the pressure beneath the foot refers to the examination and evaluation of the pressure field acting between the surface of the plantar and any supporting surface during walking, running or any other locomotion activity. Measurements obtained from such studies are very useful in various ways. According to Orlin & McPoil (2000), an indication of the function of foot and ankle during any human locomotion activity can be obtained by examining plantar pressure parameters. They are also considered to be very useful measurements in the process of diagnosing several types of foot disorders (Rai & Aggarwal 2006). Therefore, experts can use them to identify and diagnose deformities, and then treat any associated gait abnormality. They can also be used to inform strategies to prevent pressure ulcers in diabetes (Hessert et al. 2005).

### 2.3.1 Pressure measuring systems

A number of techniques and devices have been developed to record plantar pressure parameters. They can be categorised into two types of systems.

#### 2.3.1.1 Platform systems

Platform systems are one kind of system used to quantify the human plantar pressure during walking or standing. According to Akhtaruzzaman et al. (2016), these electronic devices are a particular type of carpet belonging to the so-called floor sensors systems. They are used to capture pressure data using sensors located along the floor on a platform (Muro-De-La-Herran et al. (2014) and Abdul Razak et al. (2012)). One of these systems is shown in Figure 2.2.


Figure 2.2: Pressure Platform System

#### 2.3.1.2 In-shoe systems

According to Muro-De-La-Herran et al. (2014) and Cordero et al. (2004), in-shoe systems are one of the wearable sensors systems used to record the distribution of the pressure under the foot sole. The sensors in this case are trimmable and can be embedded in the shoe to recognise the ground reaction force during gait (Tao et al. 2012). After fitting these sensors in suitably sized shoes, they are to be connected to a computer to capture the data through a software such as F-Scan research (Motawea et al. 2019). That means the obtained pressure measurements reflect the interface between the foot and the shoe (Abdul Razak et al. 2012). Figures 2.3 Figure 2.4 show one of these systems.

Figure 2.3: In-sole Sensor


Figure 2.4: In-shoe Pressure System

### 2.3.2 Pressure data capturing techniques

Experts and researchers in human gait analysis, particularly those in the medical sectors, have used several procedures and protocols to capture data from people with various gait conditions. Thus, the focus of this section is exploring those procedures considered to be the most familiar in the past 10 years.

Generally, two systems are used to record human gait data: platform systems and in-shoe systems. Consequently, this review is conducted according to the system used. The first group of articles to be reviewed are those which utilised platform systems, while the second group includes published works which used in-shoe systems. Furthermore, protocol followed to collect data provides a mean of classifying articles into sub-groups.

Let us begin with those who used platform systems. McKay et al. (2017) and Hafer et al. (2013) used a platform system and the two step protocol to collect data. With this protocol, participants hit the platform with their foot on the second step. McKay et al. (2017) recruited 1000 healthy individuals. The participants completed five walks at their comfortable walking speed. Then, three walks were collected using the two-step protocol. The number of participants in Hafer et al. (2013) on the other hand was 22. They walked 10 times on the platform and the above protocol was used to gather the data.

Another protocol was used by Rao et al. (2011) and Maetzler et al. (2010); the mid-gait protocol. In this method, a pressure platform is placed midway of either an 8 or 10-m walkway (Wearing et al. 1999). In the first study, 50 subjects were recruited to record a minimum of three and maximum of five steps by using mid-gait protocol (Rao et al. 2011). Maetzler et al. (2010) used a platform system and the mid-gait protocol to collect pressure parameter values from 23 healthy volunteers.

Other researchers used different protocols. Bus & de Lange (2005) used a platform, which was located in the middle of a 6.7-m wooden walkway, to compare three protocols. Those were: 1-step, 2-steps and 3-step protocols in which platform contact was made on the first, second, or third step. Ten repeated trails per protocol were collected from fourteen diabetic patients. Butterworth et al. (2015) studied some gait characteristics in obese and non-obese individuals. Nine participants were also examined to investigate the reliability of plantar pressure measurements by three researchers (Gurney et al. 2008). In the later two studies, the researchers used a platform to collect plantar pressure data. Five steps were taken prior to and following platform contact, and these were repeated five times. Putti et al. (2008) studied plantar pressure parameters of fifty-three healthy volunteers. They placed a platform at the centre of a flat 10m walkway at ground level. Subject were asked to walk at normal speed while four steps were recorded. The whole process was carried out twice.

The second group of articles contains those for which in-shoe systems were used to collect data. The length of the walkway used in each study will be used to classify these articles into sub-groups.

Six works published from 2007 to 2017 reported using walkways approximately 10m long (Chuckpaiwong et al. (2008), Arts & Bus (2011), Khodaei et al. (2017), Rao & Carter (2012), Putti et al. (2007) and Putti et al. (2010)). The authors of the first work used a 10m walkway to record the pressure data of 50 healthy adults (Chuckpaiwong et al. 2008). Each subject completed five trials. Rao & Carter (2012) also utilised a 10m walkway. They recruited fifteen adults to record plantar pressure parameters from ten steps.

A 10m walkway was also used to record the pressures of thirty diabetic patients in Arts & Bus (2011). They used the above mentioned mid-gait protocol with the in-shoe system to record 20 steps. Multiple trials were performed by the subjects. Khodaei et al. (2017) used a 9m walkway. They recruited 25 adults to walk for three laps down the walkway at a self-selected speed. The five middle steps were chosen for analysis. Furthermore, Putti and colleagues asked a number of subjects to walk along a straight line to record eight steps during two sessions. Putti et al. (2007) recruited fifty-three subjects. While the number of subjects was twenty-eight in Putti et al. (2010).

Other researchers used different approaches to collect human gait data with in-shoe systems. Ramanathan et al. (2010) used a 26-feet long walkway to gather pressure data from twenty-seven healthy volunteers. An average of three walks was obtained from each subject and this process was repeated twice. Other researchers used 40m long corridor to extract plantar pressure parameters of 30 healthy volunteers (Martínez-Nova et al. 2007). They collected data from five to seven steps during each session, which was repeated three times. A second session was performed later. Another study that used a similar approach to Martínez-Nova et al. (2007), i.e. collecting data from about five steps during two sessions and each session with three trials, was Healy et al. (2012). Three healthy males took part in this study. They were asked to walk across a laboratory to collect data from about five or six steps. The participants completed three trials in two sessions. Another group of researchers recorded data from only the middle two steps for both walking up and down the aisle of a lab for each trial. They recruited 30 healthy female adults to do three trials (Reints et al. 2017).

The final group of articles are those in which both platform and in-shoe systems were used. Authors of three published articles reported that they used a 10m walkway with two systems to collect pressure data. Catalfamo et al. (2008) placed two platforms in the middle of a 10m walkway and inserted an in-shoe system into the subjects' shoes. The participants, 10 subjects, were asked to walk three times along the walkway. The process was repeated six times. Chevalier et al. (2010) also used the two-step gait protocol with a 10m walkway and both systems to collect data from 21 healthy subjects. Three sets of data were collected. A walkway of the same length was also used in Debbi et al. (2012) along with both pressure systems to collect data from the steps on the platform. They recruited 12 healthy subjects to perform six trials. Westphal et al. (2016) employed another approach by using the two measuring systems. They recruited 14 healthy subjects to do a total of two trials. The first trial included walking eight times over a platform; whereas, in the second trial, an in-shoe system was used to collect data from 12 steps.

From the above up-to-date critical review of the literature, it can be seen that the procedure generally used to perform a human gait analysis is to recruit a large number of participants to carry out a small number of trials by recording a small number of steps. These procedures require time, effort and money to conduct trials. Furthermore, there has not been any use of any published data to be combined with more accurate self-captured data. This method could be achieved by using a small number of participants from a large number of trails and steps.

Consequently, there is a need for more efficient protocols to collect human gait data which requires less time, efforts and money. In addition, an alternative methodology is needed to take advantage of published data which can be combined with self-captured data. Such a methodology may lead to obtain more accurate results.

## 2.4 Reliability

This section reviews topics related to reliability in human gait studies. It begins by providing a general background on reliability, and then explores some statistical techniques used to evaluate the reliability. Finally, it investigates procedures followed to evaluate reliability in human gait studies.

### 2.4.1 Overview

Reliability refers to the consistency of a measurement, performance of individuals, tool, measurement procedure or technique (Atkinson & Nevill 1998). Any measurement considered to be a reliable measurement if it produces an acceptable level of measurement variability when it is repeated over time in stable subjects (Vaz et al. 2013).

As reliability refers to the repeatability of measurement procedures, there are several factors impacting it in gait analysis (Tsushima et al. 2003). The first major factor is the variability in subjects which may occur when performing repeated gait trials. Second, the so-called measurement error which refers to the error associated with the measurement processes. There are many sources of the measurement error. It can occur because of the person who manages the measurement procedure. He/she could manage the measurement differently. In addition, the actual person taking the measurements may change from one session to another. Another source of measurement error might be in the placement of markers, the accuracy of the device itself and the movement of the markers with the movement of the subject's skin.

According to Miner-Williams (2017), the purpose behind testing reliability is to evaluate one of the following:

(a) Instrumental reliability which refers to the reliability of the measurement device

(b) Rater reliability which is the reliability of the person (researcher, observer or clinician) who administers the measurement device

(c) Response reliability which is defined as the reliability of the variable being measured.

There are two types of reliability. First, relative reliability which refers to the degree to which individuals maintain their position in a sample over repeated measurements (Henriksen et al. 2004). Second, absolute reliability which refers to the degree to which repeated measurements vary for individuals (Liaw et al. 2008). In other words, experts use relative reliability to calculate the agreement level between test-retest measurements whereas, absolute reliability is used to evaluate measurement errors caused by repeated measurements.

Due to the impact of error, it is unusual to obtain any measurement that is perfectly reliable. Therefore, any observed score can be assumed to have two components, a true score and an error component. Since the true score is not calculable, the true value of the reliability cannot be known. The statistical concept of variance, however, can be used to estimate such value (Bruton et al. 2000). Thus, reliability can be expressed as a ratio of the variance of the true score to the total variance (Weir 2005). This ratio can be represented by:

$$R = \frac{\sigma_t^2}{\sigma_t^2 + \sigma_e^2} \tag{2.1}$$

Where:
$\sigma_t^2$ is the true score variance, and
$\sigma_e^2$ is the error variance.

This ratio can be quantified by various statistical tools, as shown in the next section.

### 2.4.2 Statistical tools for evaluating reliability

Several statistical tools are used to examine reliability. Some are used for relative reliability, and others for absolute reliability.

#### 2.4.2.1 Intra-class correlation coefficient (ICC)

Intra-class correlation coefficient (ICC) is a statistical technique used to evaluate the reliability among several measurements by using the data variation that is due to subjects and then compare it to the other portion of that portion due to raters (Gwet 2014). In other words, the ICC is the correlation of two or more measurements from the same subject (Shrout & Fleiss 1979). It is used to evaluate relative reliability. There are three means of calculating ICC depending on the design of the reliability study. Design is determined by two elements. First, the model of the ICC. The following are the three possible models of ICC:

(i) Model 1: each subject is assessed by a different set of randomly selected raters

(ii) Model 2: each subject is assessed by each rater, and the raters are randomly selected

(iii) Model 3: each subject is assessed by each rater, but the raters are the only raters of interest.

The other element that should be defined is the form of the ICC. Two scenarios are used here, namely calculating the reliability on a single measurement or two or more measurements recorded by different raters by taking the average. Before formulating the ICC, we need to be familiar with the one-way and two-way ANOVA tables as shown in Tables 2.1 and 2.2.

Table 2.1: One-way ANOVA

| **Source of Variation** | **Mean Square (MS)** |
|---|---|
| Between subjects | BMS |
| Within subjects | WMS |

Table 2.2: Two-way ANOVA

| Source of Variation | Mean Square (MS) |
|---|---|
| Between subjects | BMS |
| Between raters | RMS |
| Error | EMS |

Thus, below are the cases of ICC (Rankin & Stokes 1998)[1]:

1. Case 1

   Each subject is assessed by a different set of randomly selected raters, and the reliability is calculated as follows:

   (a) From a single measurement:

   $$ICC(1^2, 1^3) = \frac{BMS - WMS}{BMS + (k-1)\,WMS} \tag{2.2}$$

   (b) By taking an average of k measurements:

   $$ICC(1, k) = \frac{BMS - WMS}{BMS} \tag{2.3}$$

2. Case 2

   Each subject is assessed by each rater who belongs to a random sample selected from a large population of raters, and reliability is calculated as follows:

   (a) From a single measurement:

   $$ICC(2, 1) = \frac{BMS - EMS}{BMS + (k-1)EMS + k(RMS - EMS)/n} \tag{2.4}$$

[1] k = number of raters/measurements; n = number of subjects

[2] model number

[3] form type

(b) By taking an average of k measurements:

$$ICC(2,k) = \frac{BMS - EMS}{BMS + k(RMS - EMS)/n} \tag{2.5}$$

3. Case 3

   Each subject is assessed by each of the raters who are the only raters of interest, and reliability is calculated as follows:

   (a) From a single measurement:

$$ICC(3,1) = \frac{BMS - EMS}{BMS + (k-1)EMS} \tag{2.6}$$

   (b) By taking an average of k measurements:

$$ICC(3,k) = \frac{BMS - EMS}{BMS} \tag{2.7}$$

#### 2.4.2.2 Coefficient of variation (CV)

The coefficient of variation (CV) is an estimate of measurement error (Bruton et al. 2000). It can be calculated according to Lexell & Downham (2005) for data from repeated measurements on a single case as follows:

$$ME = \frac{SD_{diff}}{\sqrt{n}} \tag{2.8}$$

Where, $SD_{diff}$ is the standard deviation of the differences.

$$CV = \frac{ME}{mean} \times 100 \tag{2.9}$$

#### 2.4.2.3 Standard error of measurement (SEM)

Standard error of measurement (SEM) is an indicator of absolute reliability. It represents the standard deviation of measurement errors. According to Atkinson &

Nevill (1998), the SEM is given by:

$$SEM = SD\sqrt{1 - ICC} \tag{2.10}$$

Where:
SD is the sample standard deviation, and
ICC is the intra-class correlation coefficient.

Due to the fact that SEM is expressed in actual units, we can say the smaller the SEM, the greater the reliability.

#### 2.4.2.4 Repeatability coefficient (CR)

Another useful index of the absolute reliability (measurement error) is the coefficient of reliability. It can be calculated by multiplying the within-subject standard deviation ($S_w$) or the standard error of measurement (SEM) by 2.77 ($\sqrt{2} \times 1.96$) (Vaz et al. (2013) and Lexell & Downham (2005)). Thus:

$$CR = 2.77 \times S_w(SEM) \tag{2.11}$$

## 2.5 Reliability examination in gait analysis

As mentioned earlier, reliability is examined to evaluate the variability between different devices, techniques and performances of the same subjects or raters. In gait analysis studies, experts test the reliability to evaluate the variability of one of the following:

1. Different measurement devices to collect gait data such as new devices against

existing ones

2. Different techniques or methodologies used to collect data from subjects such as:

   (a) several numbers of trials or steps

   (b) various protocols

3. Pre-past performances of subjects who have had surgeriy, injury or treatment

4. Different orthoses that are used by people who suffer from special medical problems such as a new orthoses against old ones.

As a result, several procedures can be applied to test reliability in gait analysis studies. The purpose of the study is the key point to procedure choice. Thus, it can be one of the following scenarios

### 2.5.1 One way reliability evaluation

Suppose we aim to evaluate the reliability of one measurement device (such as a pressure platform), orthosis or methodology. According to Almarwani et al. (2016), Gurney et al. (2008), Izquierdo-Renau et al. (2017), König et al. (2014), Putti et al. (2008) and Brach et al. (2008), the procedures to do such test might be described as:

1. Recruiting some subjects to perform the test

2. Doing the test for more than one trial during more than one session.

For example, let us assume that 10 subjects were recruited to do five trials for two sessions for the purpose of testing the reliability of a measurement device. Thus,

Table 2.3 presents the data set with assumed values of any gait parameter (just for clarification purpose) [4].

Table 2.3: Assumed reliability data

| Subjects | Session 1 | | | Session 2 | | |
|---|---|---|---|---|---|---|
| | **Trial 1** | **...** | **Trial 5** | **Trial 1** | **...** | **Trial 5** |
| **1** | 23 | ... | 32 | 29 | ... | 54 |
| **⋮** | ⋮ | ... | ⋮ | ⋮ | ... | ⋮ |
| **10** | 14 | ... | 26 | 15 | ... | 27 |

Now, there are two scenarios that can be used to apply the abovementioned statistical tools to discuss reliability quantitatively (Almarwani et al. (2016), Gurney et al. (2008), Izquierdo-Renau et al. (2017), König et al. (2014), Putti et al. (2008), Brach et al. (2008) and Hafer et al. (2013)).

#### 2.5.1.1 Intra-session reliability

The intra-session reliability test is used to determine the reliability between measures taken in the same session. In this case, the ICC, for instance, is calculated for the five trials for each session. Thus, the results would look like those in Table 2.4.

[4] All data of the three tables in this section are assumed and used to clarify the procedures.

Table 2.4: Intra-session reliability

| Subjects | Session 1 | Session 2 |
| --- | --- | --- |
| | **ICC** | **ICC** |
| **1** | 0.67 | 0.85 |
| **⋮** | ⋮ | ⋮ |
| **10** | 0.59 | 0.34 |

#### 2.5.1.2 Inter-session reliability

The inter-session reliability test is utilised to evaluate the reliability between measures taken in different sessions. To calculate ICC, we need fist to average the trials of each session and then find the ICC for the two resulting columns. Therefore, the result would be similar to those in Table 2.5:

Table 2.5: Inter-session reliability

| Subjects | **ICC** |
| --- | --- |
| **1** | 0.67 |
| **⋮** | ⋮ |
| **10** | 0.59 |

### 2.5.2 Several ways reliability evaluation

The above procedures can be followed to evaluate the reliability of two or more measurement devices, orthoses or methodologies. You just replace the sessions with devices and everything will be same for the two scenarios intra and inter-reliability. Furthermore, this may also apply for the case of pre-post performances of the same subjects.

# Chapter 3

# Methodology

This chapter describes how the objectives of the research were achieved. The main focus is the introduction of new protocols to collect highly accurate human gait data. It also demonstrates the statistical techniques (utilised throughout this thesis) to propose an alternative methodology to carry out human gait analysis. The statistical techniques are used to: 1) combine data from self-captured trials and published works by allocating weights for each measurement, and 2) calculate the final results from the weighted data. In addition, this chapter describes the materials and devices used during the data collecting procedures. The sampling strategy and conditions of participants are also introduced. Lastly, the chapter presents a workflow explaining the processes used in the innovative alternative statistical methodology in human gait analysis.

## 3.1 Data Collecting

The human gait data required for this research were captured from three groups of participants: 1) healthy young adults, 2) healthy older adults and 3) obese adults. The general attention of this research is on plantar pressure parameters, which may contain: contact area (CA), peak pressure (PP), pressure time integral (PTI), maximum force (MF), mean force (MeF), force time integral (FTI) and mean area (MeA). These parameters were collected from several regions of the human plantar surface. There are four main regions of the human foot: rearfoot (RF) , midfoot (MF), forefoot (FF) and toes (TO), as shown in Figure 3.1. Depending on the purpose of the study, these main regions can be divided into smaller regions. Therefore, each of the three studies included in this thesis targeted several pressure parameters and various foot regions, as appears in Chapter 4, 5 and 6. As required by the proposed methodology, human gait data from published works were also collected.

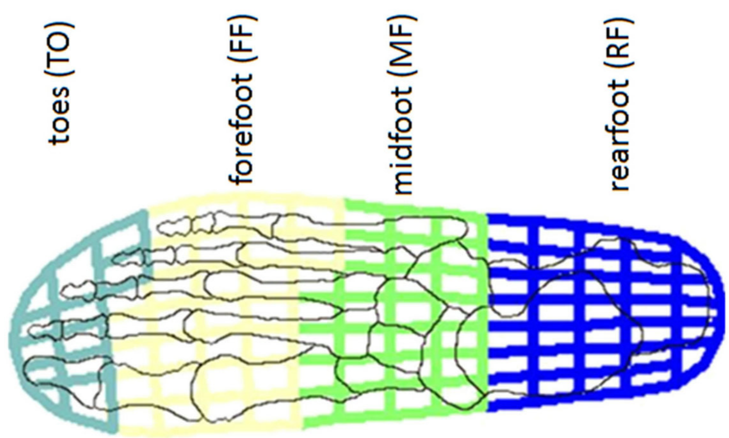


Figure 3.1: The four foot regions (Giacomozzi & Uccioli 2013)

The rest of this chapter are organised as: Section 3.1.1 introduces the number and conditions of participants recruited to conduct each study of this thesis. In addition, it presents the required systems and softwares used to collect and analyse the data.

Section 3.1.2 and Section 3.1.3 illustrate the data collection methods employed by the proposed methodology. Section 3.2 introduces the innovative statistical methodology. Sections 3.3 and 3.4 present the sampling strategy and research work flow, respectively.

### 3.1.1 Materials

Three studies were conducted by recruiting 15 voluntary participants for the self-captured trials and collecting data from published works. For the self-captured trials, each study had five participants. Therefore, three groups of participants were involved in this research: five healthy young adults, five healthy older adults and five obese adults. All chosen volunteers had no issues that could impact their ability to walk normally. Before the trials began, age, height and weight for each participant were recorded. Each participant was asked to walk at a self-selected speed along a 10m walkway in a basement laboratory at the University of Southern Queensland. Participants wore appropriate sized shoes with 300E F-Scan insole sensors sandwiched between the foot and the inside shoe. The sensors were connected to a computer (as shown in Figure 3.2). F-Scan Research Software was utilised to record and extract pressure beneath the foot data. IBM SPSS Statistica 23 and Microsoft Excel were also used to analyse the data.

Figure 3.2: F-Scan system

The dimensions of each pressure insole are overall length: 327.2 mm, overall width: 313.7 mm, tab length: 182.6 mm and thickness: 0.178 mm. In addition, each insole has a number of sensels equals to 954 and the sensel density is 3.9 sensels/cm$^2$. Figure 3.3 shows the pressure insole used in this research.

Figure 3.3: F-Scan insole

Ethics approval was obtained from the Human Research Ethics Committee at the University of Southern Queensland (Application ID: H18REA162) as shown in Appendix A.

### 3.1.2 Data acquisition from published works

The first source of data for this research is published articles, i.e. those whose focus is on the parameters of the pressure beneath the foot. The most comprehensive articles, in terms of the number of pressure parameters and foot regions, were considered to collect published data of the three groups of participants.

### 3.1.3 Data acquisition from gait trials

In-shoe systems with F-Scan Research Software were used in the gait trials. Prior to each testing session,the system was calibrated for each participant using their bodyweight. The trials were performed with three groups of participants: 1) healthy young adults, 2) healthy older adults and 3) obese adults. Each group had five participants. At the beginning of each session, the researchers explained the procedures to the participants and then asked them to attend a practice session so they could familiarise themselves with the procedures.

During the real walking tests, each participant was asked to walk at his\her normal speed on a 10-m walkway in a basement laboratory. To eliminate the effect of acceleration and deceleration of the body at the start and end of the walking trials, the middle 6 m was designated for the process of data collecting (Burnfield et al. 2004). Therefore, data of the sixth, seventh and eighth steps were analysed. Every participant performed an average of 12 trials (walks) per session, and the whole session was repeated for a second time after one week. Thus, we had 12 trials per session. To satisfy the independence assumption of statistical analysis, Data from only one foot was analysed (Menz (2005), Khodaei et al. (2017) and Menz & Morris (2006)).

Two protocols were followed to collect the data:

1. One-step protocol which means extracting data from only one step out of the whole 10-m walk. The seventh step was used in this protocol.

2. Three-steps-mean protocol which refers to the method of obtaining data by taking the average of the three steps, i.e. 6th, 7th and 8th steps, out of the whole 10-m walk.

## 3.2 Data Analysis

According to the suggested statistical methodology, the first phase in the process of data analysis was computing the mean and standard deviation (SD) of the suggested two protocols, and then comparing these with those from published works. Comparison happens into two ways:

1. Comparing standard deviations of the results of the published data with those of the one-step protocol
2. Comparing standard deviations of the results of the published data with those of the three-steps-mean protocol.

These comparisons aimed to determine which of the suggested protocols is the more accurate, so it could be used in the next phase. The second phase combined data from the two sources, i.e. self-captures trials (the more accurate protocol) and published works. This was carried out by assigning weights for each parameters of the published and self-captured data. The next step is calculating statistical measures from the weighted data.

Furthermore, a number of the above-mentioned statistical measurements were used to evaluate reliability: such as intra-class correlation coefficients (ICC), coefficient of variation (CV), standard error of measurement (SEM) or repeatability coefficient (CR).

### 3.2.1 Weighting techniques

Before talking about weights and how to assign weights to any observation or measurement, it is best to review the concept of precision in statistics. When there are several measurements of the same quantity from different samples, the degree of closeness of these measurements to each other is defined as precision. The closer the values of such measurements, the higher the precision. Two of the common measures of the precision are standard deviation ($\sigma$) and variance ($\sigma^2$) (Brown 2007). Thus, a measurement with large variance has low precision. So, the value of variance goes in the opposite direction of precision. Another measure of precision, called the weight of an observation, is related to the precision directly. That means the higher precision of any measurement the higher the weight. Correspondingly, the weight of any observation can be expressed as a quantity that is inversely proportional to the variance of that observation (Mikhail & Gracie 1981).

According to Borenstein et al. (2011), the weight assigned to any measurement is given by:

$$w = \frac{1}{\sigma^2} \tag{3.1}$$

Where: $\sigma^2$ is the variance.

In addition, allocating weights can be achieved using other statistical measurements, as follows:

- **ICC**

  Intra-class correlation coefficient (ICC) can be used to assign weights for data from several sources using:

$$w = \frac{1}{ICC} \tag{3.2}$$

- **CV**

  Assigning weights for measurements obtained from sources of different accuracy can be achieved using the coefficient of variation (CV) as:

$$w = \frac{1}{CV} \tag{3.3}$$

- **SEM**

  The values of the standard error of measurement (SEM) of data from several sources might be employed to allocate weights for each measurement as:

$$w = \frac{1}{SEM^2} \tag{3.4}$$

- **CR**

  Giving weight for measurements from various sources can be achieved by using the repeatability coefficient (CR). The formula is given by:

$$w = \frac{1}{CR} \tag{3.5}$$

### 3.2.2 Data combining

The final phase of the proposed alternative statistical methodology is calculating the final results from the weighted data. As was pointed out in Borenstein et al. (2011), Mikhail & Gracie (1981), Sutton et al. (2000) and Cochran (1937), the weights allocated for the data from both sources, i.e. published and self-captured data, are used to calculate the weighted mean and standard error by using the formulas:

- The weighted mean (M) is given by:

$$M = \frac{\sum_{i=1}^{k} w_i m_i}{\sum_{i=1}^{k} w_i} \tag{3.6}$$

  Where:

  $k$ is the number of data sources,

  $w_i$ is the assigned weight for a measurement from source i,

  $m_i$ is the mean of a measurement from source i.

- The standard error (SE) in this case can be calculated as follows:

$$SE = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}} \tag{3.7}$$

Where:

$w_i$ is the assigned weight for a measurement from source i.

## 3.3 Sampling Strategy

Both types of data, published and self-captured, were gathered depending on the group of participants. The first two groups of participants, healthy young adults and healthy older adults, did not have any medical conditions that affect their ability to walk normally. The third group, however, involved obese adults. World Health Organisation age group classifications were used to identify the age range of the first two groups. For the healthy adults group, published and self-captured data were obtained from people aged (20-59 years). The age of those who belonged to the healthy older adults group was (60-75 years). However, participants of the third group had to be above 20 years old with a BMI $\geq$ 30 kg/m$^2$.

## 3.4 Workflow

Figure 3.4 summarises the main steps of conducting each study in the thesis using the innovative alternative statistical methodology.

## 3.5 Summary

This chapter demonstrates the new alternative statistical methodology proposed for conducting human gait analysis. It introduces new protocols to collect gait data with higher accuracy. It also illustrates how to use statistical techniques to combine data from different sources, and then to calculate the final results from the combined data. In addition, this chapter outlines the equipment used and procedures needed to perform the research.

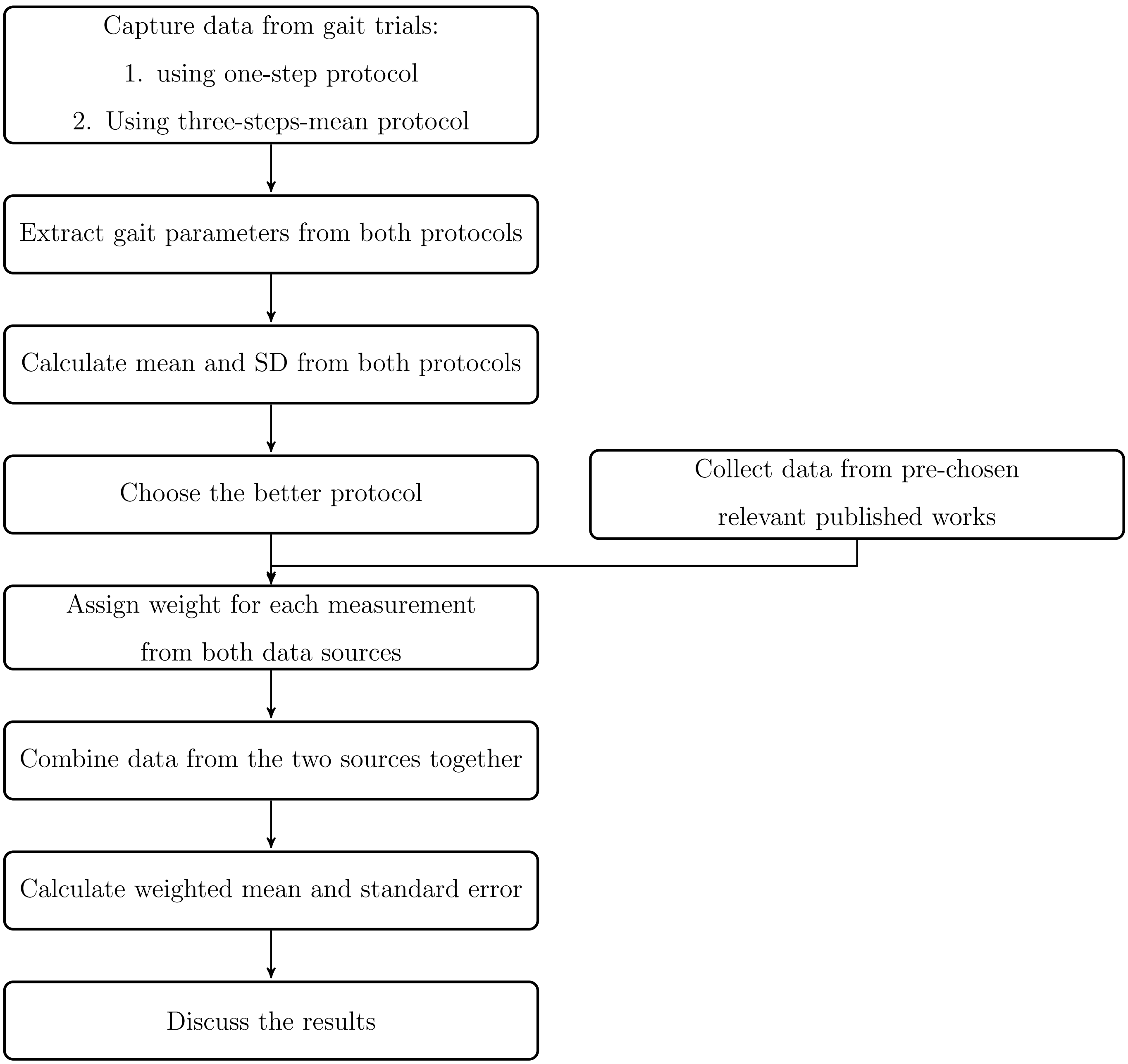


Figure 3.4: Workflow of the main steps of each study in the thesis

# Chapter 4

# Study I: Healthy Young Adults

The purpose of this chapter is to discuss the first study applying the innovative statistical methodology introduced in Chapter 3 and to study the methodology's effectiveness. This study also aimed to establish range values for pressure parameters using the innovative statistical methodology. Therefore, this chapter evaluates the study of several gait parameters of healthy subjects aged between 20 and 60 years. The main motivation for studying the gait characteristics for healthy adults is that professionals and experts in related fields, such as medicine, sport and security, require a good understanding for normal gait. This is especially important for those who work in the medical sectors so they can more efficiently diagnose and treat patients, who suffer from abnormality in walking.

## 4.1 Materials and Data Collecting

Five healthy participants were recruited voluntarily for this study. None of the participants suffered any health conditions which could affect their ability to walk normally. They were not suffering from any pain in their feet, had no previous injuries and/or surgery to the lower limbs. Furthermore, none had any kind of disability or other clinical condition that could lead to an abnormal gait.

Age, height and weight were recorded. The average age, height and weight of the participants was 39.44 years old (range 32-46 years), 170.6 cm (range 162-186 cm) and 80.4 kg (range 57-103 kg), respectively.

After inserting the 3000E F-Scan in-shoe sensors inside of appropriately sized shoes for each participant, participants were asked to walk at their normal speed along a 10-m long walkway in a laboratory setting. Twelve trials were recorded for each participants. Each session was repeated after one week. Data from the sixth, seventh and eighth steps from both sessions were then recorded.

### 4.1.1 Data from published works

To make this study as comprehensive as it could be, published articles with several numbers of foot regions and pressure parameters were considered. Thus, Ramanathan et al. (2010) was chosen to be the main source of the published data for this study. It was chosen for two reasons:

- Of the published articles, it reported the highest number of pressure characteristics (eight).
- Of the published articles, it examined these eight pressure characteristics for the highest number of foot regions (ten).

In this study, 27 healthy males, with no issues that might affect their gait in any way, were recruited to study the parameters. While wearing appropriately sized shoes with insole sensors sandwiched inside them, participants were asked to walk along a 26-feet long walkway at their natural self-selected speed. Two sessions were performed. From each session an average of three trials were recorded for each person. The results (mean and standard deviation) of the left foot are displayed in Table 4.1.

Table 4.1: Results of the left foot from Ramanathan et al. (2010)

| Masks | CA ($cm^2$) | | MeF (N) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | | MF (N) | | MeA ($cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 46.20 | 3.00 | 227.90 | 26.90 | 178.70 | 23.90 | 60.90 | 14.00 | 162.70 | 30.50 | 536.80 | 58.10 | 29.10 | 4.10 |
| **Midfoot** | 26.40 | 2.20 | 74.20 | 15.50 | 88.10 | 22.70 | 40.80 | 26.60 | 53.70 | 20.50 | 137.30 | 24.00 | 16.90 | 2.30 |
| **MTH1** | 14.00 | 1.50 | 56.60 | 13.10 | 166.40 | 32.80 | 48.50 | 13.10 | 40.10 | 12.50 | 147.00 | 33.90 | 8.50 | 1.70 |
| **MTH2** | 14.00 | 1.10 | 62.20 | 12.80 | 161.60 | 33.60 | 47.50 | 13.10 | 44.00 | 12.80 | 156.10 | 32.40 | 9.50 | 1.60 |
| **MTH3** | 7.50 | 0.60 | 35.50 | 7.00 | 155.30 | 28.70 | 47.70 | 12.10 | 25.20 | 6.20 | 84.00 | 12.90 | 5.50 | 0.90 |
| **MTH4** | 7.20 | 0.40 | 30.70 | 6.20 | 124.90 | 19.10 | 42.70 | 10.30 | 21.80 | 5.10 | 67.10 | 9.50 | 5.50 | 0.90 |
| **MTH5** | 6.70 | 0.50 | 22.40 | 4.20 | 94.00 | 15.50 | 34.70 | 7.60 | 16.00 | 3.40 | 48.30 | 7.20 | 4.70 | 0.70 |
| **Hallux** | 8.60 | 1.30 | 30.50 | 9.20 | 173.70 | 44.60 | 41.80 | 13.20 | 21.30 | 7.40 | 100.40 | 27.20 | 4.40 | 1.10 |
| **2nd toe** | 8.10 | 1.90 | 15.50 | 3.80 | 91.50 | 22.00 | 22.10 | 5.20 | 10.70 | 2.90 | 51.50 | 11.00 | 3.40 | 0.90 |
| **3-5 toes** | 8.50 | 1.70 | 12.70 | 4.30 | 93.30 | 29.70 | 25.60 | 9.40 | 8.80 | 2.90 | 38.70 | 8.20 | 3.60 | 1.00 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

In addition, three more published articles, that reported a significant number of pressure parameters of a high number of foot regions, were also considered.

First, four pressure parameters of interest from 10 foot regions were investigated in Putti et al. (2007). They recruited 53 volunteers with no history of feet problems. Insoles were inserted into shoes and then connected to the software. Data were collected in two sessions. Eight walks per session were recorded and each walk contained eight steps. The results (mean and standard deviation) of this study are shown in Table 4.2

Table 4.2: Results from Putti et al. (2007)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 41.54 | 6.4 | 264.3 | 44.1 | 64.58 | 12.7 | 145.03 | 37.2 |
| **Midfoot** | 21.58 | 6.3 | 109.0 | 38.5 | 39.18 | 17.5 | 43.08 | 27.9 |
| **MTH1** | 12.29 | 2.3 | 248.0 | 70.1 | 65.43 | 22.3 | 48.05 | 19.1 |
| **MTH2** | 12.67 | 2.0 | 246.5 | 48.3 | 65.52 | 16.3 | 52.19 | 16.2 |
| **MTH3** | 6.79 | 1.0 | 224.7 | 50.4 | 62.96 | 16.3 | 28.97 | 10.1 |
| **MTH4** | 6.26 | 1.1 | 161.0 | 49.7 | 49.29 | 17.1 | 20.08 | 8.8 |
| **MTH5** | 6.23 | 1.3 | 141.6 | 58.4 | 46.53 | 20.4 | 18.93 | 9.6 |
| **Hallux** | 7.86 | 1.4 | 280.4 | 83.0 | 60.29 | 20.6 | 24.83 | 10.7 |
| **2nd toe** | 7.72 | 1.8 | 138.9 | 55.3 | 28.93 | 13.3 | 9.89 | 5.1 |
| **3-5 toes** | 7.28 | 2.3 | 121.3 | 45.5 | 29.52 | 12.9 | 9.19 | 5.4 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral

Putti et al. (2008) also reported the same four parameters of the 10 foot regions. For this study, 53 healthy volunteers were recruited. Participants were asked to walk along a 10m walkway with a platform located in the centre of the walkway. Data from four footsteps were collected and the whole session was repeated for second time. Table 4.3 shows the results (mean and standard deviation) of this study.

Last, three pressure parameters from eight foot regions of interest were studied by Maetzler et al. (2010). They located a platform in the middle of a 10m walkway to collect pressure data from 23 healthy volunteers and the results (mean and standard deviation) are shown in Table 4.4.

Table 4.3: Results from Putti et al. (2008)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 34.5 | 5.2 | 313 | 77 | 73 | 25 | 105 | 31 |
| **Midfoot** | 23.8 | 9.8 | 113 | 37 | 33 | 15 | 28 | 23 |
| **MTH1** | 13.6 | 2.4 | 277 | 90 | 87 | 37 | 52 | 20 |
| **MTH2** | 10.5 | 1.8 | 361 | 104 | 107 | 35 | 54 | 15 |
| **MTH3** | 11.5 | 1.9 | 330 | 84 | 104 | 30 | 57 | 16 |
| **MTH4** | 9.5 | 1.4 | 233 | 67 | 80 | 30 | 35 | 13 |
| **MTH5** | 5.9 | 1.0 | 151 | 78 | 50 | 30 | 14 | 7 |
| **Hallux** | 10.4 | 2.1 | 321 | 141 | 81 | 49 | 26 | 13 |
| **2nd toe** | 3.6 | 1.1 | 158 | 73 | 37 | 24 | 5 | 3 |
| **3-5 toes** | 7.3 | 2.4 | 111 | 54 | 29 | 22 | 6 | 5 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral

Table 4.4: Results from Maetzler et al. (2010)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 33.8 | 4.8 | 323 | 93 | 77 | 33 |
| **Midfoot** | 19.2 | 8.8 | 104 | 43 | 28 | 15 |
| **MTH1** | 12.5 | 2.2 | 275 | 98 | 84 | 31 |
| **MTH2** | 9.8 | 1.6 | 407 | 146 | 122 | 40 |
| **MTH3** | 10.6 | 1.7 | 345 | 96 | 113 | 29 |
| **MTH4** | 9.3 | 1.4 | 238 | 87 | 82 | 28 |
| **MTH5** | 6.0 | 1.1 | 141 | 66 | 46 | 20 |
| **Hallux** | 11.2 | 2.1 | 435 | 202 | 103 | 57 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral

### 4.1.2 Data from self-captured trials

As mentioned in 4.1, five healthy participants were involved in the trials. Following the most comprehensive study of Ramanathan et al. (2010) and to extract the required data, the foot was divided into ten regions: heel, midfoot, first metatarsal (MTH1), second metatarsal (MTH2), third metatarsal (MTH3), fourth metatarsal (MTH4), fifth metatarsal (MTH5), hallux, second toe and third-fifth toes as shown in Figure 4.1.

Values of the seven most clinically relevant parameters were extracted for each of the three steps for 24 trials. The parameters were: contact area (CA) $cm^2$, mean force (MeF) N, peak pressure (PP) kPa, pressure-time integral (PTI) kPa s, force-time integral (FTI) N s, maximum force (MF) N and mean area (MeA) $cm^2$.

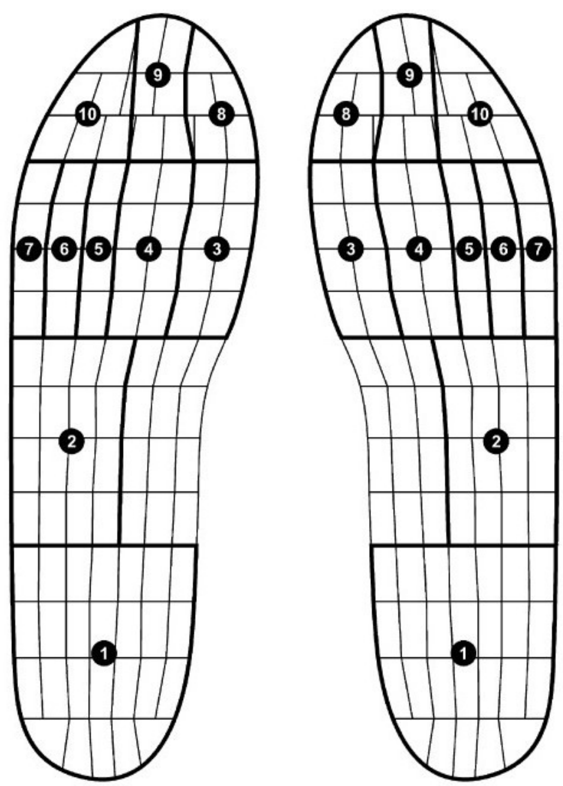


Figure 4.1: 10 regions of the foot (Putti et al. 2007)

Table 4.5: Results of one-step protocol from healthy young participants

| Masks | CA ($cm^2$) | | MeF (N) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | | MF (N) | | MeA ($cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 36.81 | 0.31 | 253.04 | 14.13 | 398.52 | 24.70 | 55.26 | 2.61 | 164.97 | 7.05 | 718.50 | 49.59 | 16.82 | 0.80 |
| **Midfoot** | 19.49 | 1.72 | 56.30 | 6.55 | 560.55 | 136.58 | 35.26 | 3.56 | 36.97 | 3.95 | 133.82 | 13.07 | 7.80 | 0.90 |
| **MTH1** | 7.52 | 0.28 | 30.34 | 3.41 | 225.84 | 25.09 | 32.07 | 3.04 | 20.54 | 4.05 | 100.15 | 11.03 | 2.76 | 0.31 |
| **MTH2** | 6.25 | 0.12 | 40.35 | 3.54 | 299.78 | 28.78 | 51.72 | 4.39 | 27.35 | 5.53 | 117.34 | 11.05 | 3.05 | 0.17 |
| **MTH3** | 7.75 | 0.10 | 56.38 | 3.93 | 391.18 | 31.66 | 60.50 | 4.19 | 38.59 | 6.56 | 159.62 | 10.36 | 4.00 | 0.21 |
| **MTH4** | 7.03 | 0.08 | 54.61 | 3.67 | 362.38 | 26.50 | 64.44 | 3.70 | 37.00 | 4.14 | 145.90 | 7.67 | 4.08 | 0.22 |
| **MTH5** | 15.68 | 0.36 | 100.56 | 12.37 | 282.49 | 22.02 | 52.07 | 3.76 | 65.91 | 8.07 | 249.37 | 23.66 | 9.62 | 1.06 |
| **Hallux** | 9.41 | 0.25 | 33.31 | 4.07 | 310.78 | 33.36 | 23.63 | 2.20 | 22.11 | 5.39 | 177.00 | 16.35 | 2.65 | 0.28 |
| **2nd toe** | 2.44 | 0.30 | 3.77 | 0.69 | 122.58 | 12.48 | 12.11 | 1.52 | 2.43 | 0.43 | 23.43 | 3.49 | 0.46 | 0.08 |
| **3-5 toes** | 2.88 | 0.64 | 2.55 | 0.95 | 86.67 | 16.23 | 9.08 | 2.36 | 3.10 | 7.03 | 17.08 | 4.85 | 0.41 | 0.13 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

Table 4.6: Results of three-steps-mean protocol from healthy young participants

| Masks | CA ($cm^2$) | | MeF (N) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | | MF (N) | | MeA ($cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 36.80 | 0.23 | 254.59 | 11.83 | 400.60 | 25.88 | 55.36 | 2.35 | 165.19 | 6.30 | 725.63 | 36.38 | 16.90 | 0.69 |
| **Midfoot** | 19.61 | 1.42 | 56.66 | 4.74 | 533.33 | 80.31 | 35.11 | 2.10 | 36.87 | 2.83 | 134.51 | 10.82 | 7.83 | 0.80 |
| **MTH1** | 7.48 | 0.27 | 30.88 | 2.30 | 226.75 | 15.32 | 32.25 | 2.03 | 20.40 | 1.74 | 100.73 | 6.52 | 2.77 | 0.29 |
| **MTH2** | 6.24 | 0.10 | 40.45 | 2.40 | 298.38 | 20.89 | 51.69 | 3.32 | 26.63 | 2.16 | 116.67 | 7.88 | 3.03 | 0.17 |
| **MTH3** | 7.74 | 0.08 | 56.33 | 3.35 | 389.05 | 30.03 | 60.34 | 3.92 | 37.49 | 2.82 | 158.48 | 8.89 | 3.98 | 0.19 |
| **MTH4** | 7.03 | 0.05 | 54.77 | 2.74 | 358.52 | 25.81 | 64.21 | 3.49 | 36.36 | 2.19 | 144.94 | 6.78 | 4.09 | 0.17 |
| **MTH5** | 15.71 | 0.20 | 100.64 | 7.88 | 281.76 | 13.87 | 52.22 | 2.44 | 65.54 | 5.35 | 248.88 | 13.02 | 9.67 | 0.75 |
| **Hallux** | 9.41 | 0.18 | 33.41 | 2.56 | 310.99 | 27.48 | 23.54 | 1.45 | 21.57 | 1.89 | 175.01 | 13.87 | 2.67 | 0.23 |
| **2nd toe** | 2.43 | 0.20 | 3.70 | 0.49 | 120.73 | 8.61 | 12.00 | 0.91 | 2.36 | 0.31 | 22.84 | 2.30 | 0.45 | 0.06 |
| **3-5 toes** | 2.81 | 0.50 | 2.40 | 0.66 | 84.11 | 10.69 | 8.92 | 1.89 | 2.07 | 2.45 | 16.20 | 3.22 | 0.40 | 0.10 |

MTH: metatarsal head; SD: standard deviation; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

The format of mean and standard deviation (SD) was used to summarise the data of the two proposed protocols (as explained in Section 3.1.3). Table 4.5 contains the results of the one-step protocol (7th step) and Table 4.6 displays the results of the three-steps-mean protocol (sixth, seventh and eighth step).

Data from the three-steps-mean protocol were examined for outliers and distribution. The Shapiro-Wilks test was used to investigate normality. According to this test, the hypothesis of normality is rejected when the test value is $\leq 0.05$. Thus, the data were plausibly normally distributed. Table B.1 to Table B.7 in Appendix B.1 show the results of the Shapiro-Wilks test for all 70 parameters examined in this study. In addition, outlier detection gave acceptable results, where only 9 (12.8 %) of 70 examined parameters have outliers. Figure B.1 to Figure B.70 in Appendix B.2 display the results of the outlier detection tests.

## 4.2 Innovative Statistical Methodology for Healthy Young Adult Participants

With the current proposed alternative statistical methodology based on combining highly accurate self-captured and published gait data, the accuracy of the proposed two protocols was examined to decide which protocol is more accurate. The most accurate protocol was then to be used in the combining procedure.

A quick look at the standard deviations from data of the two proposed protocols, i.e. SD's in Tables 4.5 and 4.6, shows that the three-steps-mean protocol is more accurate than the one-step protocol. The standard deviations in the three-steps-mean protocol were smaller in 69 of 70 (98%) parameters. It is also clear that three-steps-mean protocol is more accurate than other protocols used in the published works.

By comparing standard deviations of the three-steps-mean protocol with that of the published works, i.e. SD's from Table 4.6 with that from Table 4.1, 4.2, 4.3 and 4.4, we found that:

- **Ramanthan 2010:**
  64 of 70 (91.4 %) of the standard deviations were smaller in the results of the three-steps-mean protocol
- **Putti 2007:**
  39 of 40 (97.5 %) of the standard deviations were smaller in the results of the three-steps-mean protocol
- **Putti 2008:**
  39 of 40 (97.5 %) of the standard deviations were smaller in the results of the three-steps-mean protocol
- **Maetzler 2010:**
  23 of 24 (95.8 %) of the standard deviations were smaller in the results of the three-steps-mean protocol

Which again proves that the three-steps-mean protocol is more accurate.

### 4.2.1 Combining data from self-captured trials and one publication at a time

Data from the earlier mentioned published works and self-captured trials were combined by assigning weights for each measurement. The alternative statistical methodology was applied individually in this section, which means weighting and combining data of the self-captured trials with those of each published work individually.

Therefore, this section uses the alternative statistical methodology to individually combine the data of self-captured trials with those of the above four publications. Which requires:

1. Combine self-captured data with data of Ramanathan et al. (2010).
2. Combine self-captured data with data of Putti et al. (2007).
3. Combine self-captured data with data of Putti et al. (2008).
4. Combine self-captured data with data of Maetzler et al. (2010).

Equations (3.1 and 3.3) were used to assign weights. After that, equations (3.6 and 3.7) were used to calculate the weighted means (M) and standard errors (SE), respectively.

#### 4.2.1.1 Combining by variance

Variance was the first statistical measure used in the procedures of weighting and combining data. Equation 3.1 was used to assign weights by variance. Consequently, Table 4.7 shows the weighting values of each parameter in the self-captured data. In addition, Table 4.8, Table 4.9, Table 4.10 and Table 4.11 display the weighting values of published works, i.e. Ramanathan et al. (2010), Putti et al. (2007), Putti et al. (2008) and Maetzler et al. (2010), respectively.

The first results of the alternative statistical methodology are shown in Table 4.12 in the format of weighted mean and standard error, i.e. by using equations (3.6 and 3.7). These were calculated by combining the self-captured data with that from Ramanathan et al. (2010), i.e. by using Table 4.7 and Table 4.8.

By comparing them with the results of Ramanathan et al. (2010) (Table 4.1), we can clearly see that the procedure of combining more accurate self-captured data with published data produced more accurate results, where the standard errors of the proposed alternative methodology of all parameters 70 out of 70 (100%) were smaller than standard deviations of the published work.

Table 4.7: Weighting values for the three-steps-mean protocol by variance for healthy young participants

| Mask | CA (cm²) | | | | | MeF (N) | | | | | PP (kPa) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 36.80 | 0.23 | 0.05 | 18.75 | 689.89 | 254.59 | 11.83 | 140.02 | 0.01 | 1.82 | 400.60 | 25.88 | 669.99 | 0.0015 | 0.60 |
| **Midfoot** | 19.61 | 1.42 | 2.01 | 0.50 | 9.74 | 56.66 | 4.74 | 22.48 | 0.04 | 2.52 | 533.33 | 80.31 | 6449.60 | 0.0002 | 0.08 |
| **MTH1** | 7.48 | 0.27 | 0.07 | 13.59 | 101.66 | 30.88 | 2.30 | 5.30 | 0.19 | 5.82 | 226.75 | 15.32 | 234.56 | 0.0043 | 0.97 |
| **MTH2** | 6.24 | 0.10 | 0.01 | 107.99 | 673.94 | 40.45 | 2.40 | 5.77 | 0.17 | 7.01 | 298.38 | 20.89 | 436.24 | 0.0023 | 0.68 |
| **MTH3** | 7.74 | 0.08 | 0.01 | 176.12 | 1363.60 | 56.33 | 3.35 | 11.20 | 0.09 | 5.03 | 389.05 | 30.03 | 902.09 | 0.0011 | 0.43 |
| **MTH4** | 7.03 | 0.05 | 0.00 | 387.78 | 2724.34 | 54.77 | 2.74 | 7.48 | 0.13 | 7.32 | 358.52 | 25.81 | 666.16 | 0.0015 | 0.54 |
| **MTH5** | 15.71 | 0.20 | 0.04 | 24.12 | 379.05 | 100.64 | 7.88 | 62.09 | 0.02 | 1.62 | 281.76 | 13.87 | 192.32 | 0.0052 | 1.47 |
| **Hallux** | 9.41 | 0.18 | 0.03 | 31.74 | 298.60 | 33.41 | 2.56 | 6.57 | 0.15 | 5.08 | 310.99 | 27.48 | 755.33 | 0.0013 | 0.41 |
| **2nd toe** | 2.43 | 0.20 | 0.04 | 26.18 | 63.50 | 3.70 | 0.49 | 0.24 | 4.18 | 15.46 | 120.73 | 8.61 | 74.18 | 0.0135 | 1.63 |
| **3-5 toes** | 2.81 | 0.50 | 0.25 | 4.03 | 11.33 | 2.40 | 0.66 | 0.44 | 2.28 | 5.48 | 84.11 | 10.69 | 114.20 | 0.0088 | 0.74 |

| Mask | PTI (kPa s) | | | | | FTI (N s) | | | | | MF (N) | | | | | MeA (cm²) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 55.36 | 2.35 | 5.50 | 0.18 | 10.06 | 165.19 | 6.30 | 39.74 | 0.025 | 4.16 | 725.63 | 36.38 | 1323.64 | 0.001 | 0.55 | 16.90 | 0.69 | 0.47 | 2.13 | 35.99 |
| **Midfoot** | 35.11 | 2.10 | 4.40 | 0.23 | 7.97 | 36.87 | 2.83 | 7.99 | 0.125 | 4.62 | 134.51 | 10.82 | 117.00 | 0.009 | 1.15 | 7.83 | 0.80 | 0.63 | 1.58 | 12.35 |
| **MTH1** | 32.25 | 2.03 | 4.14 | 0.24 | 7.79 | 20.40 | 1.74 | 3.02 | 0.332 | 6.76 | 100.73 | 6.52 | 42.45 | 0.024 | 2.37 | 2.77 | 0.29 | 0.08 | 12.20 | 33.78 |
| **MTH2** | 51.69 | 3.32 | 11.02 | 0.09 | 4.69 | 26.63 | 2.16 | 4.66 | 0.215 | 5.72 | 116.67 | 7.88 | 62.04 | 0.016 | 1.88 | 3.03 | 0.17 | 0.03 | 36.60 | 110.97 |
| **MTH3** | 60.34 | 3.92 | 15.38 | 0.07 | 3.92 | 37.49 | 2.82 | 7.96 | 0.126 | 4.71 | 158.48 | 8.89 | 78.99 | 0.013 | 2.01 | 3.98 | 0.19 | 0.04 | 27.25 | 108.55 |
| **MTH4** | 64.21 | 3.49 | 12.18 | 0.08 | 5.27 | 36.36 | 2.19 | 4.79 | 0.209 | 7.60 | 144.94 | 6.78 | 46.00 | 0.022 | 3.15 | 4.09 | 0.17 | 0.03 | 34.68 | 141.96 |
| **MTH5** | 52.22 | 2.44 | 5.96 | 0.17 | 8.76 | 65.54 | 5.35 | 28.65 | 0.035 | 2.29 | 248.88 | 13.02 | 169.40 | 0.006 | 1.47 | 9.67 | 0.75 | 0.56 | 1.78 | 17.23 |
| **Hallux** | 23.54 | 1.45 | 2.11 | 0.47 | 11.13 | 21.57 | 1.89 | 3.58 | 0.279 | 6.02 | 175.01 | 13.87 | 192.42 | 0.005 | 0.91 | 2.67 | 0.23 | 0.05 | 18.82 | 50.15 |
| **2nd toe** | 12.00 | 0.91 | 0.83 | 1.20 | 14.40 | 2.36 | 0.31 | 0.09 | 10.540 | 24.89 | 22.84 | 2.30 | 5.27 | 0.190 | 4.33 | 0.45 | 0.06 | 0.00 | 251.12 | 113.96 |
| **3-5 toes** | 8.92 | 1.89 | 3.57 | 0.28 | 2.50 | 2.07 | 2.45 | 5.98 | 0.167 | 0.35 | 16.20 | 3.22 | 10.35 | 0.097 | 1.57 | 0.40 | 0.10 | 0.01 | 91.93 | 36.42 |

MTH: metatarsal head; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area; SD: standard deviation; var: variance; wi: weight

Table 4.8: Weighting values for Ramanathan 2010 data by variance

| Mask | CA ($cm^2$) | | | | | MeF (N) | | | | | PP (kPa) | | | | | PTI (kPa s) | | | | | FTI (N s) | | | | | MF (N) | | | | | MeA ($cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 46.20 | 3.00 | 9.00 | 0.11 | 5.13 | 227.90 | 26.90 | 723.61 | 0.00 | 0.31 | 178.70 | 23.90 | 571.21 | 0.0018 | 0.31 | 60.90 | 14.00 | 196.00 | 0.01 | 0.31 | 162.70 | 30.50 | 930.25 | 0.001 | 0.17 | 536.80 | 58.10 | 3375.61 | 0.000 | 0.16 | 29.10 | 4.10 | 16.81 | 0.06 | 1.73 |
| **Midfoot** | 26.40 | 2.20 | 4.84 | 0.21 | 5.45 | 74.20 | 15.50 | 240.25 | 0.00 | 0.31 | 88.10 | 22.70 | 515.29 | 0.0019 | 0.17 | 40.80 | 26.60 | 707.56 | 0.00 | 0.06 | 53.70 | 20.50 | 420.25 | 0.002 | 0.13 | 137.30 | 24.00 | 576.00 | 0.002 | 0.24 | 16.90 | 2.30 | 5.29 | 0.19 | 3.19 |
| **MTH1** | 14.00 | 1.50 | 2.25 | 0.44 | 6.22 | 56.60 | 13.10 | 171.61 | 0.01 | 0.33 | 166.40 | 32.80 | 1075.84 | 0.0009 | 0.15 | 48.50 | 13.10 | 171.61 | 0.01 | 0.28 | 40.10 | 12.50 | 156.25 | 0.006 | 0.26 | 147.00 | 33.90 | 1149.21 | 0.001 | 0.13 | 8.50 | 1.70 | 2.89 | 0.35 | 2.94 |
| **MTH2** | 14.00 | 1.10 | 1.21 | 0.83 | 11.57 | 62.20 | 12.80 | 163.84 | 0.01 | 0.38 | 161.60 | 33.60 | 1128.96 | 0.0009 | 0.14 | 47.50 | 13.10 | 171.61 | 0.01 | 0.28 | 44.00 | 12.80 | 163.84 | 0.006 | 0.27 | 156.10 | 32.40 | 1049.76 | 0.001 | 0.15 | 9.50 | 1.60 | 2.56 | 0.39 | 3.71 |
| **MTH3** | 7.50 | 0.60 | 0.36 | 2.78 | 20.83 | 35.50 | 7.00 | 49.00 | 0.02 | 0.72 | 155.30 | 28.70 | 823.69 | 0.0012 | 0.19 | 47.70 | 12.10 | 146.41 | 0.01 | 0.33 | 25.20 | 6.20 | 38.44 | 0.026 | 0.66 | 84.00 | 12.90 | 166.41 | 0.006 | 0.50 | 5.50 | 0.90 | 0.81 | 1.23 | 6.79 |
| **MTH4** | 7.20 | 0.40 | 0.16 | 6.25 | 45.00 | 30.70 | 6.20 | 38.44 | 0.03 | 0.80 | 124.90 | 19.10 | 364.81 | 0.0027 | 0.34 | 42.70 | 10.30 | 106.09 | 0.01 | 0.40 | 21.80 | 5.10 | 26.01 | 0.038 | 0.84 | 67.10 | 9.50 | 90.25 | 0.011 | 0.74 | 5.50 | 0.90 | 0.81 | 1.23 | 6.79 |
| **MTH5** | 6.70 | 0.50 | 0.25 | 4.00 | 26.80 | 22.40 | 4.20 | 17.64 | 0.06 | 1.27 | 94.00 | 15.50 | 240.25 | 0.0042 | 0.39 | 34.70 | 7.60 | 57.76 | 0.02 | 0.60 | 16.00 | 3.40 | 11.56 | 0.087 | 1.38 | 48.30 | 7.20 | 51.84 | 0.019 | 0.93 | 4.70 | 0.70 | 0.49 | 2.04 | 9.59 |
| **Hallux** | 8.60 | 1.30 | 1.69 | 0.59 | 5.09 | 30.50 | 9.20 | 84.64 | 0.01 | 0.36 | 173.70 | 44.60 | 1989.16 | 0.0005 | 0.09 | 41.80 | 13.20 | 174.24 | 0.01 | 0.24 | 21.30 | 7.40 | 54.76 | 0.018 | 0.39 | 100.40 | 27.20 | 739.84 | 0.001 | 0.14 | 4.40 | 1.10 | 1.21 | 0.83 | 3.64 |
| **2nd toe** | 8.10 | 1.90 | 3.61 | 0.28 | 2.24 | 15.50 | 3.80 | 14.44 | 0.07 | 1.07 | 91.50 | 22.00 | 484.00 | 0.0021 | 0.19 | 22.10 | 5.20 | 27.04 | 0.04 | 0.82 | 10.70 | 2.90 | 8.41 | 0.119 | 1.27 | 51.50 | 11.00 | 121.00 | 0.008 | 0.43 | 3.40 | 0.90 | 0.81 | 1.23 | 4.20 |
| **3-5 toes** | 8.50 | 1.70 | 2.89 | 0.35 | 2.94 | 12.70 | 4.30 | 18.49 | 0.05 | 0.69 | 93.30 | 29.70 | 882.09 | 0.0011 | 0.11 | 25.60 | 9.40 | 88.36 | 0.01 | 0.29 | 8.80 | 2.90 | 8.41 | 0.119 | 1.05 | 38.70 | 8.20 | 67.24 | 0.015 | 0.58 | 3.60 | 1.00 | 1.00 | 1.00 | 3.60 |

MTH: metatarsal head; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area; SD: standard deviation; var: variance; wi: weight

Table 4.9: Weighting values for Putti 2007 data by variance

| Masks | CA ($cm^2$) | | | | | PP (kPa) | | | | | PTI (kPa s) | | | | | FTI (N s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 41.54 | 6.4 | 40.96 | 0.02 | 1.01 | 264.3 | 44.1 | 1944.81 | 0.0005 | 0.14 | 64.58 | 12.7 | 161.29 | 0.01 | 0.40 | 145.03 | 37.2 | 1383.84 | 0.001 | 0.10 |
| **Midfoot** | 21.58 | 6.3 | 39.69 | 0.03 | 0.54 | 109.0 | 38.5 | 1482.25 | 0.0007 | 0.07 | 39.18 | 17.5 | 306.25 | 0.00 | 0.13 | 43.08 | 27.9 | 778.41 | 0.001 | 0.06 |
| **MTH1** | 12.29 | 2.3 | 5.29 | 0.19 | 2.32 | 248.0 | 70.1 | 4914.01 | 0.0002 | 0.05 | 65.43 | 22.3 | 497.29 | 0.00 | 0.13 | 48.05 | 19.1 | 364.81 | 0.003 | 0.13 |
| **MTH2** | 12.67 | 2.0 | 4.00 | 0.25 | 3.17 | 246.5 | 48.3 | 2332.89 | 0.0004 | 0.11 | 65.52 | 16.3 | 265.69 | 0.00 | 0.25 | 52.19 | 16.2 | 262.44 | 0.004 | 0.20 |
| **MTH3** | 6.79 | 1.0 | 1.00 | 1.00 | 6.79 | 224.7 | 50.4 | 2540.16 | 0.0004 | 0.09 | 62.96 | 16.3 | 265.69 | 0.00 | 0.24 | 28.97 | 10.1 | 102.01 | 0.010 | 0.28 |
| **MTH4** | 6.26 | 1.1 | 1.21 | 0.83 | 5.17 | 161.0 | 49.7 | 2470.09 | 0.0004 | 0.07 | 49.29 | 17.1 | 292.41 | 0.00 | 0.17 | 20.08 | 8.8 | 77.44 | 0.013 | 0.26 |
| **MTH5** | 6.23 | 1.3 | 1.69 | 0.59 | 3.69 | 141.6 | 58.4 | 3410.56 | 0.0003 | 0.04 | 46.53 | 20.4 | 416.16 | 0.00 | 0.11 | 18.93 | 9.6 | 92.16 | 0.011 | 0.21 |
| **Hallux** | 7.86 | 1.4 | 1.96 | 0.51 | 4.01 | 280.4 | 83.0 | 6889.00 | 0.0001 | 0.04 | 60.29 | 20.6 | 424.36 | 0.00 | 0.14 | 24.83 | 10.7 | 114.49 | 0.009 | 0.22 |
| **2nd toe** | 7.72 | 1.8 | 3.24 | 0.31 | 2.38 | 138.9 | 55.3 | 3058.09 | 0.0003 | 0.05 | 28.93 | 13.3 | 176.89 | 0.01 | 0.16 | 9.89 | 5.1 | 26.01 | 0.038 | 0.38 |
| **3-5 toes** | 7.28 | 2.3 | 5.29 | 0.19 | 1.38 | 121.3 | 45.5 | 2070.25 | 0.0005 | 0.06 | 29.52 | 12.9 | 166.41 | 0.01 | 0.18 | 9.19 | 5.4 | 29.16 | 0.034 | 0.32 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation; var: variance; wi: weight

Table 4.10: Weighting values for Putti 2008 data by variance

| Masks | CA ($cm^2$) | | | | | PP(kPa) | | | | | PTI (kPa s) | | | | | FTI (N s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 34.50 | 5.2 | 27.04 | 0.04 | 1.28 | 313.0 | 77.0 | 5929.00 | 0.0002 | 0.05 | 73.00 | 25.0 | 625.00 | 0.00 | 0.12 | 105.00 | 31.0 | 961.00 | 0.001 | 0.11 |
| **Midfoot** | 23.80 | 9.8 | 96.04 | 0.01 | 0.25 | 113.0 | 37.0 | 1369.00 | 0.0007 | 0.08 | 33.00 | 15.0 | 225.00 | 0.00 | 0.15 | 28.00 | 23.0 | 529.00 | 0.002 | 0.05 |
| **MTH1** | 13.60 | 2.4 | 5.76 | 0.17 | 2.36 | 277.0 | 90.0 | 8100.00 | 0.0001 | 0.03 | 87.00 | 37.0 | 1369.00 | 0.00 | 0.06 | 52.00 | 20.0 | 400.00 | 0.003 | 0.13 |
| **MTH2** | 10.50 | 1.8 | 3.24 | 0.31 | 3.24 | 361.0 | 104.0 | 10816.00 | 0.0001 | 0.03 | 107.00 | 35.0 | 1225.00 | 0.00 | 0.09 | 54.00 | 15.0 | 225.00 | 0.004 | 0.24 |
| **MTH3** | 11.50 | 1.9 | 3.61 | 0.28 | 3.19 | 330.0 | 84.0 | 7056.00 | 0.0001 | 0.05 | 104.00 | 30.0 | 900.00 | 0.00 | 0.12 | 57.00 | 16.0 | 256.00 | 0.004 | 0.22 |
| **MTH4** | 9.50 | 1.4 | 1.96 | 0.51 | 4.85 | 233.0 | 67.0 | 4489.00 | 0.0002 | 0.05 | 80.00 | 30.0 | 900.00 | 0.00 | 0.09 | 35.00 | 13.0 | 169.00 | 0.006 | 0.21 |
| **MTH5** | 5.90 | 1.0 | 1.00 | 1.00 | 5.90 | 151.0 | 78.0 | 6084.00 | 0.0002 | 0.02 | 50.00 | 30.0 | 900.00 | 0.00 | 0.06 | 14.00 | 7.0 | 49.00 | 0.020 | 0.29 |
| **Hallux** | 10.40 | 2.1 | 4.41 | 0.23 | 2.36 | 321.0 | 141.0 | 19881.00 | 0.0001 | 0.02 | 81.00 | 49.0 | 2401.00 | 0.00 | 0.03 | 26.00 | 13.0 | 169.00 | 0.006 | 0.15 |
| **2nd toe** | 3.60 | 1.1 | 1.21 | 0.83 | 2.98 | 158.0 | 73.0 | 5329.00 | 0.0002 | 0.03 | 37.00 | 24.0 | 576.00 | 0.00 | 0.06 | 5.00 | 3.0 | 9.00 | 0.111 | 0.56 |
| **3-5 toes** | 7.30 | 2.4 | 5.76 | 0.17 | 1.27 | 111.0 | 54.0 | 2916.00 | 0.0003 | 0.04 | 29.00 | 22.0 | 484.00 | 0.00 | 0.06 | 6.00 | 5.0 | 25.00 | 0.040 | 0.24 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation; var: variance; wi: weight

Table 4.11: Weighting values for Maetzler 2010 data by variance

| Masks | CA ($cm^2$) | | | | | PP(kPa) | | | | | PTI (kPa s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 33.80 | 4.8 | 23.04 | 0.04 | 1.47 | 323.0 | 93.0 | 8649.00 | 0.0001 | 0.04 | 77.00 | 33.0 | 1089.00 | 0.001 | 0.07 |
| **Midfoot** | 19.20 | 8.8 | 77.44 | 0.01 | 0.25 | 104.0 | 43.0 | 1849.00 | 0.0005 | 0.06 | 28.00 | 15.0 | 225.00 | 0.004 | 0.12 |
| **MTH1** | 12.50 | 2.2 | 4.84 | 0.21 | 2.58 | 275.0 | 98.0 | 9604.00 | 0.0001 | 0.03 | 84.00 | 31.0 | 961.00 | 0.001 | 0.09 |
| **MTH2** | 9.80 | 1.6 | 2.56 | 0.39 | 3.83 | 407.0 | 146.0 | 21316.00 | 0.0000 | 0.02 | 122.00 | 40.0 | 1600.00 | 0.001 | 0.08 |
| **MTH3** | 10.60 | 1.7 | 2.89 | 0.35 | 3.67 | 345.0 | 96.0 | 9216.00 | 0.0001 | 0.04 | 113.00 | 29.0 | 841.00 | 0.001 | 0.13 |
| **MTH4** | 9.30 | 1.4 | 1.96 | 0.51 | 4.74 | 238.0 | 87.0 | 7569.00 | 0.0001 | 0.03 | 82.00 | 28.0 | 784.00 | 0.001 | 0.10 |
| **MTH5** | 6.00 | 1.1 | 1.21 | 0.83 | 4.96 | 141.0 | 66.0 | 4356.00 | 0.0002 | 0.03 | 46.00 | 20.0 | 400.00 | 0.003 | 0.12 |
| **Hallux** | 11.20 | 2.1 | 4.41 | 0.23 | 2.54 | 435.0 | 202.0 | 40804.00 | 0.0000 | 0.01 | 103.00 | 57.0 | 3249.00 | 0.000 | 0.03 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation; var: variance; wi: weight

Table 4.12: Results of the alternative statistical methodology by variance for healthy young participants (combined with Rammanthan's results)

| Masks | CA (cm²) | | MeF (N) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | | MF (N) | | MeA (cm²) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** |
| **Heel** | 36.85 | 0.23 | 250.26 | 10.83 | 280.82 | 17.56 | 55.51 | 2.31 | 165.09 | 6.17 | 672.44 | 30.84 | 17.23 | 0.68 |
| **Midfoot** | 21.61 | 1.19 | 58.16 | 4.53 | 121.04 | 21.84 | 35.14 | 2.09 | 37.18 | 2.80 | 134.98 | 9.86 | 8.80 | 0.75 |
| **MTH1** | 7.69 | 0.27 | 31.65 | 2.27 | 215.95 | 13.88 | 32.63 | 2.01 | 20.77 | 1.72 | 102.38 | 6.40 | 2.93 | 0.28 |
| **MTH2** | 6.30 | 0.10 | 41.19 | 2.36 | 260.25 | 17.74 | 51.44 | 3.22 | 27.11 | 2.13 | 118.87 | 7.65 | 3.10 | 0.16 |
| **MTH3** | 7.74 | 0.07 | 52.46 | 3.02 | 266.87 | 20.75 | 59.14 | 3.73 | 35.38 | 2.57 | 134.50 | 7.32 | 4.05 | 0.19 |
| **MTH4** | 7.03 | 0.05 | 50.85 | 2.50 | 207.57 | 15.35 | 62.00 | 3.30 | 34.10 | 2.01 | 118.66 | 5.52 | 4.14 | 0.17 |
| **MTH5** | 14.43 | 0.19 | 39.71 | 3.71 | 198.28 | 10.34 | 50.58 | 2.32 | 30.24 | 2.87 | 95.30 | 6.30 | 7.02 | 0.51 |
| **Hallux** | 9.39 | 0.18 | 33.20 | 2.47 | 273.21 | 23.40 | 23.76 | 1.45 | 21.56 | 1.83 | 159.61 | 12.36 | 2.74 | 0.23 |
| **2nd toe** | 2.49 | 0.19 | 3.89 | 0.48 | 116.85 | 8.02 | 12.31 | 0.90 | 2.45 | 0.31 | 24.04 | 2.25 | 0.47 | 0.06 |
| **3-5 toes** | 3.26 | 0.48 | 2.64 | 0.65 | 85.17 | 10.06 | 9.57 | 1.85 | 4.87 | 1.87 | 19.20 | 2.99 | 0.43 | 0.10 |

MTH: metatarsal head; M: weighted mean; SE: standard error; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

Table 4.13 includes the results of one of the plantar pressure parameters investigated in this study, i.e. maximum force (MF). It can be used to compare the accuracy of all the three techniques, i.e. the three-steps-mean protocol, the most commonly used protocol in published works and the innovative statistical methodology.

Once again, it can be seen that the alternative statistical methodology performed better than others with regard to accuracy, where standard errors of the alternative statistical methodology are smaller than those of the other techniques in all ten regions of the foot.

Table 4.13: Results of maximum force of three protocols for healthy young participants (using Rammanthan's data)

| Masks | three-steps-mean | | published | | alternative | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **M** | **SE** |
| **Heel** | 725.63 | 36.38 | 536.80 | 58.10 | 672.44 | 30.84 |
| **Midfoot** | 134.51 | 10.82 | 137.30 | 24.00 | 134.98 | 9.86 |
| **MTH1** | 100.73 | 6.52 | 147.00 | 33.90 | 102.38 | 6.40 |
| **MTH2** | 116.67 | 7.88 | 156.10 | 32.40 | 118.87 | 7.65 |
| **MTH3** | 158.48 | 8.89 | 84.00 | 12.90 | 134.50 | 7.32 |
| **MTH4** | 144.94 | 6.78 | 67.10 | 9.50 | 118.66 | 5.52 |
| **MTH5** | 248.88 | 13.02 | 48.30 | 7.20 | 95.30 | 6.30 |
| **Hallux** | 175.01 | 13.87 | 100.40 | 27.20 | 159.61 | 12.36 |
| **2nd toe** | 22.84 | 2.30 | 51.50 | 11.00 | 24.04 | 2.25 |
| **3-5 toes** | 16.20 | 3.22 | 38.70 | 8.20 | 19.20 | 2.99 |

MTH: metatarsal head; SD: standard deviation; M: weighted mean; SE: standard error

Data from the three other mentioned published works were also individually combined with the self-captured data using variance. Table 4.14, Table 4.15 and Table 4.16 show the results of the alternative statistical methodology by combining data from the self-captured trials with that from Putti et al. (2007), Putti et al. (2008) and Maetzler et al. (2010), respectively.

Once again the alternative statistical methodology proved its effectiveness. A very quick comparison between Table 4.14 and Table 4.2, Table 4.15 and Table 4.3, and finally Table 4.16 and 4.4 shows that it is more accurate in all (100%) the parameters studied.

Table 4.14: Results of alternative statistical methodology for healthy young participants (combined with Putti 2007 results)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|
| | M | SE | M | SE | M | SE | M | SE |
| **Heel** | 33.80 | 4.8 | 323.0 | 93.0 | 77.00 | 33.0 | 164.63 | 6.22 |
| **Midfoot** | 19.20 | 8.8 | 104.0 | 43.0 | 28.00 | 15.0 | 36.93 | 2.81 |
| **MTH1** | 12.50 | 2.2 | 275.0 | 98.0 | 84.00 | 31.0 | 20.62 | 1.73 |
| **MTH2** | 9.80 | 1.6 | 407.0 | 146.0 | 122.00 | 40.0 | 27.08 | 2.14 |
| **MTH3** | 10.60 | 1.7 | 345.0 | 96.0 | 113.00 | 29.0 | 36.87 | 2.72 |
| **MTH4** | 9.30 | 1.4 | 238.0 | 87.0 | 82.00 | 28.0 | 35.41 | 2.12 |
| **MTH5** | 6.00 | 1.1 | 141.0 | 66.0 | 46.00 | 20.0 | 54.49 | 4.68 |
| **Hallux** | 11.20 | 2.1 | 435.0 | 202.0 | 103.00 | 57.0 | 21.67 | 1.86 |
| **2nd toe** | 2.49 | 0.19 | 121.16 | 8.51 | 12.08 | 0.91 | 2.39 | 0.31 |
| **3-5 toes** | 3.01 | 0.49 | 86.06 | 10.40 | 9.35 | 1.87 | 3.28 | 2.23 |

Table 4.15: Results of alternative statistical methodology for healthy young participants (combined with Putti 2008 results)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|
| | M | SE | M | SE | M | SE | M | SE |
| **Heel** | 36.79 | 0.23 | 391.71 | 24.54 | 55.51 | 2.34 | 162.80 | 6.18 |
| **Midfoot** | 19.70 | 1.40 | 186.60 | 33.60 | 35.07 | 2.08 | 36.73 | 2.80 |
| **MTH1** | 7.56 | 0.27 | 228.17 | 15.10 | 32.41 | 2.03 | 20.63 | 1.73 |
| **MTH2** | 6.25 | 0.10 | 300.80 | 20.48 | 52.19 | 3.31 | 27.19 | 2.14 |
| **MTH3** | 7.75 | 0.08 | 382.36 | 28.28 | 61.08 | 3.89 | 38.08 | 2.78 |
| **MTH4** | 7.03 | 0.05 | 342.30 | 24.08 | 64.42 | 3.47 | 36.32 | 2.16 |
| **MTH5** | 15.32 | 0.20 | 277.75 | 13.65 | 52.20 | 2.43 | 46.53 | 4.25 |
| **Hallux** | 9.42 | 0.18 | 311.36 | 26.98 | 23.59 | 1.45 | 21.67 | 1.87 |
| **2nd toe** | 2.46 | 0.19 | 121.24 | 8.55 | 12.04 | 0.91 | 2.39 | 0.31 |
| **3-5 toes** | 3.00 | 0.49 | 85.13 | 10.48 | 9.07 | 1.88 | 2.83 | 2.20 |

Table 4.16: Results of alternative statistical methodology for healthy young participants (combined with Maetzel's results)

| Masks | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | |
|---|---|---|---|---|---|---|
| | M | SE | M | SE | M | SE |
| **Heel** | 36.79 | 0.23 | 395.02 | 24.94 | 55.47 | 2.34 |
| **Midfoot** | 19.60 | 1.40 | 199.66 | 37.91 | 34.97 | 2.08 |
| **MTH1** | 7.56 | 0.27 | 227.90 | 15.13 | 32.47 | 2.03 |
| **MTH2** | 6.25 | 0.10 | 300.55 | 20.68 | 52.17 | 3.31 |
| **MTH3** | 7.75 | 0.08 | 385.12 | 28.66 | 61.29 | 3.89 |
| **MTH4** | 7.03 | 0.05 | 348.77 | 24.74 | 64.48 | 3.46 |
| **MTH5** | 15.39 | 0.20 | 275.81 | 13.57 | 52.12 | 2.42 |
| **Hallux** | 9.42 | 0.18 | 313.25 | 27.23 | 23.59 | 1.45 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SE: standard error

#### 4.2.1.2 Combining by CV

Coefficient of variation (CV) was used as another statistical measure in the data weighting and combining phases of the alternative statistical methodology. According to Lexell & Downham (2005), Menz et al. (2004), Hopkins (2000) and Ramanathan et al. (2010), the typical error might be expressed as a percentage of the mean by using the coefficient of variation (CV). It can be calculated as $(ME/mean) \times 100$, where ME is the method error and mean is the mean of the whole measurement. The standard deviation of the differences between repeated measurements is then calculated to find ME by $(SD_{diff}/\sqrt{2})$. Measurements with lower coefficient of variation values have greater repeatability.

Tables 4.17 and 4.18 show the coefficient of variation values of the three-steps-mean protocol and that of Ramanathan et al. (2010), respectively. A comparison of these two tables showed that 66 out of 70 (94.2%) of the parameters studied by using the three-steps-mean protocol have greater repeatability than those of the most common protocol used in Ramanathan et al. (2010). Which again proves that the proposed protocol yields data with higher accuracy than others.

The values of coefficient of variation were then used to assign weights, by using equation 3.3, for the published and self-captured data as shown in Tables 4.19 and 4.20. These values were then used to find weighted means and standard errors as shown in Table 4.21.

Table 4.17: Coefficient of variation (CV) of the three-steps-mean protocol

| Masks | CA ($cm^2$) | MeF (N) | PP (kPa) | PTI (kPa s) | FTI (N s) | MF (N) | MeA ($cm^2$) |
|---|---|---|---|---|---|---|---|
| **Heel** | 0.47 | 3.64 | 4.45 | 3.57 | 4.16 | 3.12 | 3.74 |
| **Midfoot** | 8.11 | 4.29 | 14.96 | 6.90 | 4.48 | 5.02 | 8.54 |
| **MTH1** | 3.07 | 4.25 | 7.88 | 4.64 | 5.79 | 6.82 | 5.86 |
| **MTH2** | 1.17 | 3.37 | 6.57 | 4.15 | 5.11 | 4.54 | 4.21 |
| **MTH3** | 1.20 | 1.69 | 4.29 | 2.91 | 4.42 | 3.78 | 4.79 |
| **MTH4** | 1.21 | 2.59 | 2.90 | 2.14 | 2.83 | 2.60 | 2.73 |
| **MTH5** | 1.30 | 10.04 | 5.21 | 5.49 | 10.42 | 6.68 | 7.67 |
| **Hallux** | 2.08 | 9.41 | 12.50 | 9.44 | 8.55 | 6.18 | 11.07 |
| **2nd toe** | 13.61 | 8.49 | 4.98 | 9.84 | 7.84 | 6.19 | 13.60 |
| **3-5 toes** | 19.50 | 20.26 | 6.12 | 13.66 | 68.32 | 14.98 | 21.33 |

MTH: metatarsal head; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

Table 4.18: Coefficient of variation (CV) of Ramanathan et al. (2010)

| Masks | CA ($cm^2$) | MeF (N) | PP (kPa) | PTI (kPa s) | FTI (N s) | MF (N) | MeA ($cm^2$) |
|---|---|---|---|---|---|---|---|
| **Heel** | 4.60 | 8.40 | 9.50 | 16.20 | 13.20 | 7.70 | 9.90 |
| **Midfoot** | 6.00 | 14.70 | 18.20 | 46.10 | 27.00 | 12.30 | 9.70 |
| **MTH1** | 7.60 | 16.30 | 13.90 | 19.00 | 22.10 | 16.30 | 14.40 |
| **MTH2** | 5.50 | 14.50 | 14.70 | 19.60 | 20.60 | 14.70 | 12.10 |
| **MTH3** | 5.50 | 13.80 | 13.10 | 18.00 | 17.50 | 10.80 | 11.10 |
| **MTH4** | 3.40 | 14.30 | 10.80 | 17.10 | 16.50 | 10.00 | 11.60 |
| **MTH5** | 5.20 | 13.30 | 11.60 | 15.50 | 15.30 | 10.60 | 10.40 |
| **Hallux** | 11.00 | 21.40 | 18.20 | 22.30 | 24.60 | 19.20 | 18.00 |
| **2nd toe** | 16.30 | 17.40 | 17.10 | 16.70 | 19.10 | 15.20 | 17.80 |
| **3-5 toes** | 13.90 | 24.10 | 22.50 | 25.90 | 23.40 | 14.90 | 19.10 |

MTH: metatarsal head; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

By comparing SE's of Table 4.21 and CV's of Table 4.18, we see that the results of the alternative statistical methodology are associated with greater accuracy than those of Ramanathan et al. (2010) in 70 of 70 (100%) pressure parameters. Thus, the suggested methodology again proves to give better performance.

Table 4.19: Weighting values for the three-steps-mean protocol by using CV for healthy young participants

| Masks | CA (cm²) | | | | MeF (N) | | | | PP (kPa) | | | | PTI (kPa s) | | | | FTI (N s) | | | | MF (N) | | | | MeA (cm²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** |
| **Heel** | 36.80 | 0.47 | 2.15 | 79.13 | 254.59 | 3.64 | 0.27 | 69.92 | 400.60 | 4.45 | 0.22 | 89.99 | 55.36 | 3.57 | 0.28 | 15.51 | 165.19 | 4.16 | 0.24 | 39.75 | 725.63 | 3.12 | 0.32 | 232.44 | 16.90 | 3.74 | 0.27 | 4.52 |
| **Midfoot** | 19.61 | 8.11 | 0.12 | 2.42 | 56.66 | 4.29 | 0.23 | 13.21 | 533.33 | 14.96 | 0.07 | 35.65 | 35.11 | 6.90 | 0.14 | 5.09 | 36.87 | 4.48 | 0.22 | 8.23 | 134.51 | 5.02 | 0.20 | 26.80 | 7.83 | 8.54 | 0.12 | 0.92 |
| **MTH1** | 7.48 | 3.07 | 0.33 | 2.43 | 30.88 | 4.25 | 0.24 | 7.27 | 226.75 | 7.88 | 0.13 | 28.79 | 32.25 | 4.64 | 0.22 | 6.95 | 20.40 | 5.79 | 0.17 | 3.52 | 100.73 | 6.82 | 0.15 | 14.77 | 2.77 | 5.86 | 0.17 | 0.47 |
| **MTH2** | 6.24 | 1.17 | 0.85 | 5.33 | 40.45 | 3.37 | 0.30 | 11.99 | 298.38 | 6.57 | 0.15 | 45.43 | 51.69 | 4.15 | 0.24 | 12.46 | 26.63 | 5.11 | 0.20 | 5.22 | 116.67 | 4.54 | 0.22 | 25.69 | 3.03 | 4.21 | 0.24 | 0.72 |
| **MTH3** | 7.74 | 1.20 | 0.83 | 6.43 | 56.33 | 1.69 | 0.59 | 33.37 | 389.05 | 4.29 | 0.23 | 90.72 | 60.34 | 2.91 | 0.34 | 20.75 | 37.49 | 4.42 | 0.23 | 8.49 | 158.48 | 3.78 | 0.26 | 41.96 | 3.98 | 4.79 | 0.21 | 0.83 |
| **MTH4** | 7.03 | 1.21 | 0.83 | 5.80 | 54.77 | 2.59 | 0.39 | 21.16 | 358.52 | 2.90 | 0.34 | 123.53 | 64.21 | 2.14 | 0.47 | 29.98 | 36.36 | 2.83 | 0.35 | 12.83 | 144.94 | 2.60 | 0.38 | 55.70 | 4.09 | 2.73 | 0.37 | 1.50 |
| **MTH5** | 15.71 | 1.30 | 0.77 | 12.11 | 100.64 | 10.04 | 0.10 | 10.03 | 281.76 | 5.21 | 0.19 | 54.10 | 52.22 | 5.49 | 0.18 | 9.50 | 65.54 | 10.42 | 0.10 | 6.29 | 248.88 | 6.68 | 0.15 | 37.28 | 9.67 | 7.67 | 0.13 | 1.26 |
| **Hallux** | 9.41 | 2.08 | 0.48 | 4.52 | 33.41 | 9.41 | 0.11 | 3.55 | 310.99 | 12.50 | 0.08 | 24.89 | 23.54 | 9.44 | 0.11 | 2.49 | 21.57 | 8.55 | 0.12 | 2.52 | 175.01 | 6.18 | 0.16 | 28.31 | 2.67 | 11.07 | 0.09 | 0.24 |
| **2nd toe** | 2.43 | 13.61 | 0.07 | 0.18 | 3.70 | 8.49 | 0.12 | 0.44 | 120.73 | 4.98 | 0.20 | 24.24 | 12.00 | 9.84 | 0.10 | 1.22 | 2.36 | 7.84 | 0.13 | 0.30 | 22.84 | 6.19 | 0.16 | 3.69 | 0.45 | 13.60 | 0.07 | 0.03 |
| **3-5 toes** | 2.81 | 19.50 | 0.05 | 0.14 | 2.40 | 20.26 | 0.05 | 0.12 | 84.11 | 6.12 | 0.16 | 13.75 | 8.92 | 13.66 | 0.07 | 0.65 | 2.07 | 68.32 | 0.01 | 0.03 | 16.20 | 14.98 | 0.07 | 1.08 | 0.40 | 21.33 | 0.05 | 0.02 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; cv: coefficient of variation; wi: weight

Table 4.20: Weighting values for Ramanathan 2010 data by using CV

| Masks | CA ($cm^2$) | | | | MeF (N) | | | | PP (kPa) | | | | PTI (kPa s) | | | | FTI (N s) | | | | MF (N) | | | | MeA ($cm^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** | **Mean** | **cv** | **wi** | **mean*wi** |
| **Heel** | 46.20 | 4.60 | 0.22 | 10.04 | 227.90 | 8.40 | 0.12 | 27.13 | 178.70 | 9.50 | 0.11 | 18.81 | 60.90 | 16.20 | 0.06 | 3.76 | 162.70 | 13.20 | 0.08 | 12.33 | 536.80 | 7.70 | 0.13 | 69.71 | 29.10 | 9.90 | 0.10 | 2.94 |
| **Midfoot** | 26.40 | 6.00 | 0.17 | 4.40 | 74.20 | 14.70 | 0.07 | 5.05 | 88.10 | 18.20 | 0.05 | 4.84 | 40.80 | 46.10 | 0.02 | 0.89 | 53.70 | 27.00 | 0.04 | 1.99 | 137.30 | 12.30 | 0.08 | 11.16 | 16.90 | 9.70 | 0.10 | 1.74 |
| **MTH1** | 14.00 | 7.60 | 0.13 | 1.84 | 56.60 | 16.30 | 0.06 | 3.47 | 166.40 | 13.90 | 0.07 | 11.97 | 48.50 | 19.00 | 0.05 | 2.55 | 40.10 | 22.10 | 0.05 | 1.81 | 147.00 | 16.30 | 0.06 | 9.02 | 8.50 | 14.40 | 0.07 | 0.59 |
| **MTH2** | 14.00 | 5.50 | 0.18 | 2.55 | 62.20 | 14.50 | 0.07 | 4.29 | 161.60 | 14.70 | 0.07 | 10.99 | 47.50 | 19.60 | 0.05 | 2.42 | 44.00 | 20.60 | 0.05 | 2.14 | 156.10 | 14.70 | 0.07 | 10.62 | 9.50 | 12.10 | 0.08 | 0.79 |
| **MTH3** | 7.50 | 5.50 | 0.18 | 1.36 | 35.50 | 13.80 | 0.07 | 2.57 | 155.30 | 13.10 | 0.08 | 11.85 | 47.70 | 18.00 | 0.06 | 2.65 | 25.20 | 17.50 | 0.06 | 1.44 | 84.00 | 10.80 | 0.09 | 7.78 | 5.50 | 11.10 | 0.09 | 0.50 |
| **MTH4** | 7.20 | 3.40 | 0.29 | 2.12 | 30.70 | 14.30 | 0.07 | 2.15 | 124.90 | 10.80 | 0.09 | 11.56 | 42.70 | 17.10 | 0.06 | 2.50 | 21.80 | 16.50 | 0.06 | 1.32 | 67.10 | 10.00 | 0.10 | 6.71 | 5.50 | 11.60 | 0.09 | 0.47 |
| **MTH5** | 6.70 | 5.20 | 0.19 | 1.29 | 22.40 | 13.30 | 0.08 | 1.68 | 94.00 | 11.60 | 0.09 | 8.10 | 34.70 | 15.50 | 0.06 | 2.24 | 16.00 | 15.30 | 0.07 | 1.05 | 48.30 | 10.60 | 0.09 | 4.56 | 4.70 | 10.40 | 0.10 | 0.45 |
| **Hallux** | 8.60 | 11.00 | 0.09 | 0.78 | 30.50 | 21.40 | 0.05 | 1.43 | 173.70 | 18.20 | 0.05 | 9.54 | 41.80 | 22.30 | 0.04 | 1.87 | 21.30 | 24.60 | 0.04 | 0.87 | 100.40 | 19.20 | 0.05 | 5.23 | 4.40 | 18.00 | 0.06 | 0.24 |
| **2nd toe** | 8.10 | 16.30 | 0.06 | 0.50 | 15.50 | 17.40 | 0.06 | 0.89 | 91.50 | 17.10 | 0.06 | 5.35 | 22.10 | 16.70 | 0.06 | 1.32 | 10.70 | 19.10 | 0.05 | 0.56 | 51.50 | 15.20 | 0.07 | 3.39 | 3.40 | 17.80 | 0.06 | 0.19 |
| **3-5 toes** | 8.50 | 13.90 | 0.07 | 0.61 | 12.70 | 24.10 | 0.04 | 0.53 | 93.30 | 22.50 | 0.04 | 4.15 | 25.60 | 25.90 | 0.04 | 0.99 | 8.80 | 23.40 | 0.04 | 0.38 | 38.70 | 14.90 | 0.07 | 2.60 | 3.60 | 19.10 | 0.05 | 0.19 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; cv: coefficient of variation; wi: weight

Table 4.21: Results of alternative statistical methodology by using CV for healthy young participants (combined with Rammanthan's results)

| Masks | CA ($cm^2$) | | MeF (N) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | | MF (N) | | MeA ($cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** |
| **Heel** | 37.66 | 0.65 | 246.52 | 1.59 | 329.80 | 1.74 | 56.36 | 1.71 | 164.59 | 1.78 | 671.16 | 1.49 | 20.24 | 1.65 |
| **Midfoot** | 23.51 | 1.86 | 60.62 | 1.82 | 332.47 | 2.87 | 35.85 | 2.45 | 39.26 | 1.96 | 135.32 | 1.89 | 12.08 | 2.13 |
| **MTH1** | 9.36 | 1.48 | 36.20 | 1.84 | 204.92 | 2.24 | 35.44 | 1.93 | 24.49 | 2.14 | 114.38 | 2.19 | 4.43 | 2.04 |
| **MTH2** | 7.60 | 0.98 | 44.56 | 1.65 | 256.14 | 2.13 | 50.96 | 1.85 | 30.08 | 2.02 | 125.97 | 1.86 | 4.70 | 1.77 |
| **MTH3** | 7.70 | 0.99 | 54.06 | 1.23 | 331.40 | 1.80 | 58.59 | 1.58 | 35.01 | 1.88 | 139.18 | 1.67 | 4.44 | 1.83 |
| **MTH4** | 7.07 | 0.94 | 51.08 | 1.48 | 309.04 | 1.51 | 61.82 | 1.38 | 34.23 | 1.56 | 128.87 | 1.44 | 4.36 | 1.49 |
| **MTH5** | 13.91 | 1.02 | 66.99 | 2.39 | 223.58 | 1.90 | 47.63 | 2.01 | 45.48 | 2.49 | 171.37 | 2.02 | 7.56 | 2.10 |
| **Hallux** | 9.28 | 1.32 | 32.52 | 2.56 | 255.10 | 2.72 | 28.97 | 2.58 | 21.50 | 2.52 | 156.84 | 2.16 | 3.33 | 2.62 |
| **2nd toe** | 5.01 | 2.72 | 7.57 | 2.39 | 114.14 | 1.96 | 15.75 | 2.49 | 4.79 | 2.36 | 31.14 | 2.10 | 1.73 | 2.78 |
| **3-5 toes** | 6.13 | 2.85 | 7.11 | 3.32 | 86.08 | 2.19 | 14.68 | 2.99 | 7.08 | 4.17 | 27.48 | 2.73 | 2.09 | 3.17 |

MTH: metatarsal head; M: weighted mean; SE: standard error; CA: contact area; MeF: mean force; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; MF: maximum force; MeA: mean area

### 4.2.2 Combining data from self-captured trials and multiple publications

The proposed alternative statistical methodology can also be used to combine data from self-captured and multiple publications. To use published works for this purpose, they must report similar parameters for the same foot regions. As a result, data from three studies, i.e. Ramanathan et al. (2010), Putti et al. (2007) and Putti et al. (2008), were combined with the self-captured data. Thus, data from four sources, i.e. self-gait trials and three publication, were combined.

To investigate the quality of the four data sources, Tables 4.1, 4.2, 4.3 and 4.6, were compared. For all 40 parameters, the results of the three-steps-mean protocol (self-captured trials) were the most accurate of all the sources. Only three parameters , i.e.

peak pressure under the region of heel,midfoot and fourth metatarsal in Ramanathan et al. (2010), had smaller standard deviations than those of the self-captured trials.

The tables that present the weighting values, i.e. Tables 4.7, 4.8, 4.9 and 4.10, were used along with Equations 3.6 and 3.7 to compute the results from the combined data. Table 4.22 shows the results as weighted mean and standard error of combing data from higher accurate self-captured trials and multiple publications.

Table 4.22: Results of alternative statistical methodology by variance for healthy young participants (combined with data of three publications)

| Masks | CA (cm) | | PP (kPa) | | PTI (kPa s) | | FTI (N S) | |
|---|---|---|---|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** |
| **Heel** | 36.85 | 0.23 | 280.04 | 15.96 | 55.94 | 2.27 | 162.34 | 5.98 |
| **Midfoot** | 21.64 | 1.16 | 117.04 | 16.90 | 35.16 | 2.06 | 37.11 | 2.77 |
| **MTH1** | 7.82 | 0.26 | 218.50 | 13.46 | 33.05 | 2.00 | 21.22 | 1.71 |
| **MTH2** | 6.33 | 0.10 | 261.18 | 16.44 | 52.41 | 3.14 | 28.05 | 2.09 |
| **MTH3** | 7.74 | 0.07 | 264.19 | 18.71 | 59.98 | 3.61 | 35.51 | 2.46 |
| **MTH4** | 7.03 | 0.05 | 204.86 | 14.33 | 61.75 | 3.23 | 33.44 | 1.94 |
| **MTH5** | 13.98 | 0.18 | 195.80 | 10.09 | 50.52 | 2.30 | 27.27 | 2.56 |
| **Hallux** | 9.38 | 0.17 | 274.91 | 22.24 | 23.99 | 1.44 | 21.73 | 1.79 |
| **2nd toe** | 2.58 | 0.19 | 117.78 | 7.89 | 12.42 | 0.90 | 2.51 | 0.30 |
| **3-5 toes** | 3.57 | 0.46 | 87.62 | 9.66 | 10.10 | 1.83 | 5.40 | 1.67 |

MTH: metatarsal head; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; M: weighted mean; SE: standard error

By comparing the results of the three published works with that of the alternative statistical methodology of multiple publications, we can see that the latter performed better and was more accurate.

## 4.3 Results

This section presents the results of studying human gait parameters of healthy young participants using the innovative alternative statistical methodology. It is divided into three subsections according to the type of statistical measure and data source used in the combining procedures.

The case of combining with one publication, the results of the alternative statistical methodology which were obtained by combining self-captured data with those of Ramanathan et al. (2010) is presented in two subsections. In addition, the results of combining self-captured data with those of the earlier mentioned three publications, Ramanathan et al. (2010), Putti et al. (2007) and Putti et al. (2008), are provided in another subsection.

### 4.3.1 Results of combining with one publication by variance

The results of the alternative statistical methodology of one publication, i.e Ramanathan et al. (2010), by using the variance were shown in Table 4.12. Therefore, it was used to present the findings in this case.

As shown in Figure 4.2, the region of the heel was found to have the largest contact area (36.85 (0.23) $cm^2$). This is followed by the midfoot and fifth metatarsal regions (21.61 (1.19) $cm^2$ and 14.43 (0.19) $cm^2$, respectively). In addition, three of the metatarsal regions had closed values for the contact area. They are the first metatarsal at (7.69 (0.27) $cm^2$), third metatarsal at (7.74 (0.07) $cm^2$) and fourth metatarsal at (7.03 (0.05) $cm^2$). The second metatarsal regions had the lowest contact area among the metatarsal areas at (6.30 (0.10) $cm^2$). In the toes regions, the largest contact area was at the hallux at (9.39 (0.18) $cm^2$), followed by the third to fifth toes and then second toe at 3.26 (0.48) $cm^2$ and 2.49 (.19)$cm^2$, respectively.

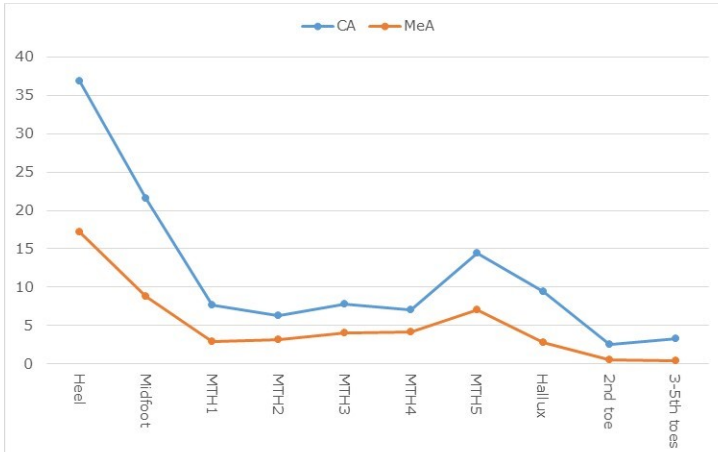


Figure 4.2: CA and MeA of combining with one publication by variance

Figure 4.3 shows the results of mean force. It was highest at the heel (250.26 (10.83) N) and lowest at the third to fifth toes region at (2.64 (0.65) N). The midfoot region had the second largest mean force (58.16 (4.53) N). The mean force was close at the first metatarsal and hallux regions at 31.65 (2.27) N and 33.20 (2.47) N, respectively. The second and fifth metatarsal regions also had close values of the mean force at 41.19 (2.36) N and 39.71 (3.71), respectively. In addition, values of the mean force were close at the third metatarsal region (52.46 (3.02) N)and the forth metatarsal region at (50.85 (2.50) N). While the second toe had the second lowest mean force at (3.89 (0.48) N).

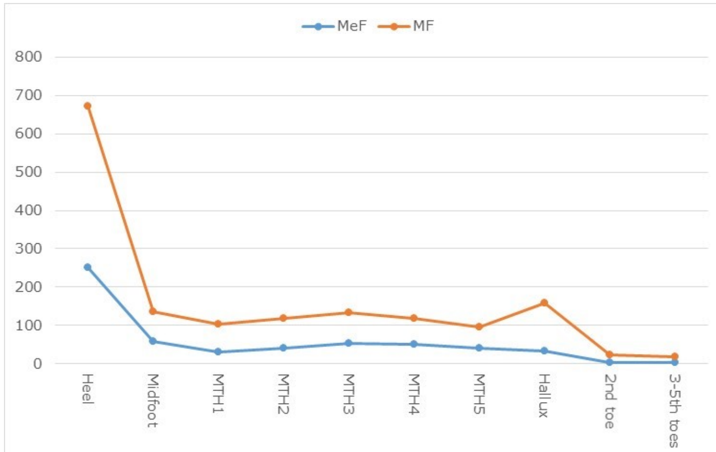


Figure 4.3: MeF and MF of combining with one publication by variance

Of the 10 regions, the highest peak pressure was under the heel (280.82 (17.56) kPa). The second and third highest values of the peak pressure were under the hallux (273.21 (23.40) kPa) and third metatarsal region (266.87 (20.75) kPa). The midfoot had a value of peak pressure at 121.04 (21.84) kPa. The rest of the metatarsal regions had peak pressures as follows: first metatarsal 215.95 (13.88) kPa, second metatarsal 260.25 (17.74) kPa, forth metatarsal 207.57 (15.35) kPa and fifth metatarsal 190.28 (10.34) kPa. Whereas, the third to fifth toes regions had the lowest peak pressure. These results are presented in Figure 4.4.


Figure 4.4: PP of combining with one publication by variance

As presented in Figure 4.5, two of the metatarsal regions had the highest pressure time integral, namely the forth metatarsal 62 (3.30) kPa s and the third metatarsal 59.14 (3.73) kPa s. The heel and midfoot regions had 55.51 (2.31) kPa s and 35.14 (2.09) kPa s, respectively. However, the values of the pressure time integral were in decreasing order in the toes regions: hallux, second and third to fifth toes.

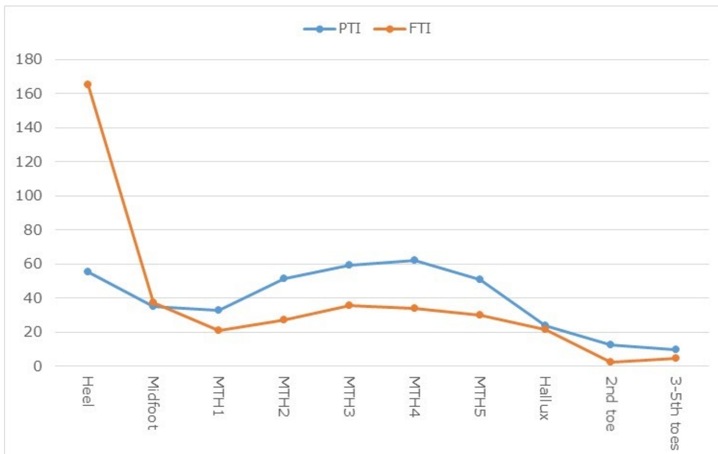


Figure 4.5: PTI and FTI of combining with one publication by variance

Figure 4.5 also presents the results of the force time integral parameter. Again, the heel had the highest force time integral at 165.09 (6.17) N s, followed by that of the midfoot at 37.18 (2.80) N s. On the other hand, the second toe had the lowest 2.45 (0.31) N s. The third and forth metatarsal regions had close force time integral 35.38 (2.57) N s and 34.10 (2.01) N s, respectively.

As was found in the mean force and shown in Figure 4.3, the highest and lowest maximum force were at the heel and third to fifth toe regions, respectively. The hallux had the second highest maximum force at 159.61 (12.36) N. In contrast, the second and forth metatarsal regions had very close maximum force at 118.87 (7.65) N and 118.66 (5.52) N, respectively.

Finally, the parameter of the mean area (displayed in Figure 4.2), the mean area was highest at the heel 17.23 (0.68) $cm^2$, followed by that of the midfoot at 8.80 (0.75) $cm^2$. The first metatarsal and hallux had very close mean areas. The third and forth metatarsal regions also had close values of mean area. Similarly, the second and third to fifth toe regions had very close mean areas 0.47 (0.06) $cm^2$ and 0.43 (0.10) $cm^2$.

### 4.3.2 Results of combining with one publication by CV

The findings from combining data from self-captured trials and one publication by using CV are shown in Table 4.21. From these results, we can see that:

for the contact area parameter, the largest values were under the areas of the heel and midfoot at 37.66 (0.65) $cm^2$ and 23.51 (1.86) $cm^2$, respectively. This was followed by the area of the fifth metatarsal at 13.91 (1.02) $cm^2$ and the first metatarsal at 9.36 (1.48) $cm^2$. The second and third to fifth toe regions had the lowest contact areas at 5.01 (2.72) $cm^2$ and 6.13 (2.85) $cm^2$, respectively. These findings were presented in Figure 4.6

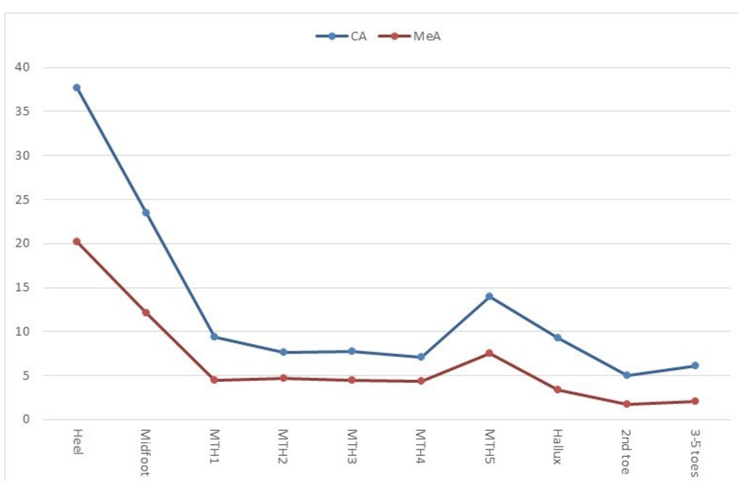


Figure 4.6: CA and MeA of combining with one publication by CV

As Figure 4.7 shows, the heel had the highest mean force at 246.52 (1.59) N. While, the second and third highest values were under the area of fifth matatarsal (66.99 (2.39) N) and midfoot 60.62 (1.82) N. In contrast, the toe areas had the lowest values of force mean parameters: hallux (32.52 (2.56) N), second toe (7.57 (2.39) N) and third to fifth toes (7.11 (3.32) N).

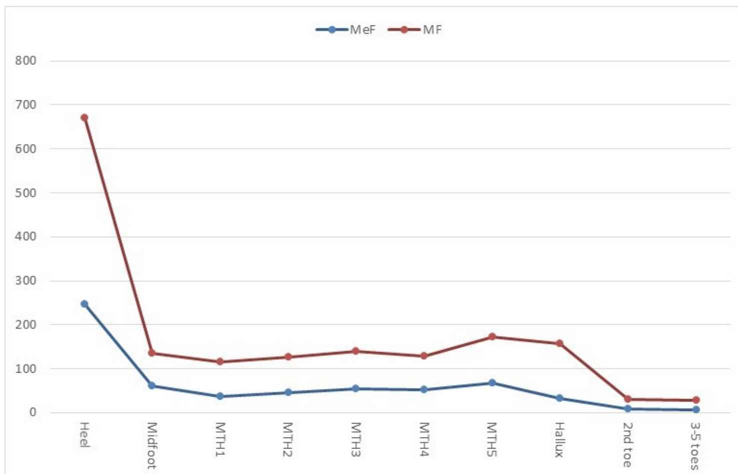


Figure 4.7: MeF and MF of combining with one publication by CV

By following Figure 4.8, the largest peak pressures were under the midfoot (332.47 (2.87) kPa), the third metatarsal (331.4 (1.80) kPa) and the heel (329.80 (1.74) kPa). On the other hand, the lowest peak pressures were under the second toe (114.14 (1.96) kPa) and third to fifth toes (86.08 (2.19) kPa).

The metatarsal areas had the highest values of pressure time integral: forth metatarsal (61.82 (1.38) kPa s) and third metatarsal (58.59 (1.58) kPa s). The toe areas had the lowest. In decreasing order hallux, second toe and third to fifth toes as displayed in Figure 4.9.

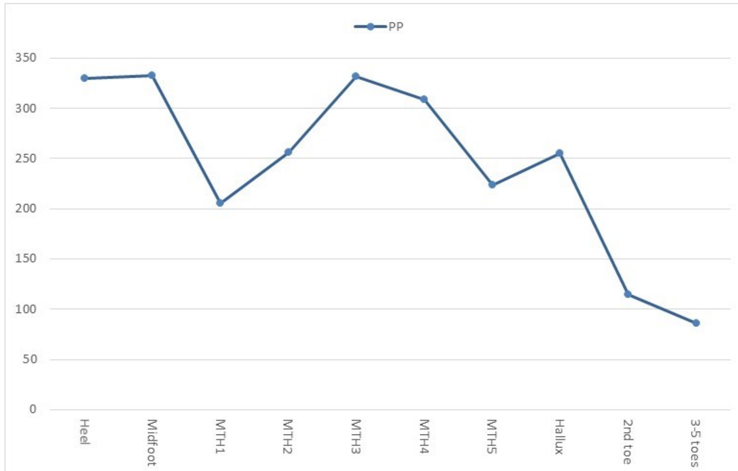


Figure 4.8: PP of combining with one publication by CV

The results of the force time integral parameter were presented in Figure 4.9. Its largest value was under the heel at (164.59 (1.78) N s). This was followed by (45.48 (2.49) N s) of the fifth metatarsal area. The lowest force time integral was under the second toe area at (4.79 (2.36) N s).


Figure 4.9: PTI and FTI of combining with one publication by CV

The same thing happened with the maximum force parameter and as shown in Figure 4.7. The heel and fifth metatarsal areas had the largest values at (671.16 (1.49) N and 45.48 (2.49) N, respectively). However, the lowest maximum force was under the area of third to fifth toes at (27.48 (2.73) N).

The first and second highest of the mean area parameter were under the heel and midfoot area, respectively. The lowest two values were under the third to forth toes and second toe area, respectively. These results were displayed in Figure 4.6.

### 4.3.3 Results of combining with multiple publications by variance

Using the alternative statistical methodology to analyse human gait parameters by combining data from self-captured and three publications yielded the following results (taken from Table 4.22).

The parameter of contact area, as shown in Figure 4.10, had the highest value under the heel (36.85 (0.23) $cm^2$). This was followed by the area of midfoot at (21.64 (1.16) $cm^2$). The smallest contact area was under the area of the second toe at (2.58 (0.19) $cm^2$).

The first and second highest values of the peak pressure parameters were under the heel at (280.04 (15.96) kPa) and the hallux at (274.91 (22.24) kPa). The areas of midfoot and third to fifth toe had the lowest values of peak pressure at 117.04 (16.90) kPa and 87.62 (9.66) kPa, respectively. These findings were presented in Figure 4.11.

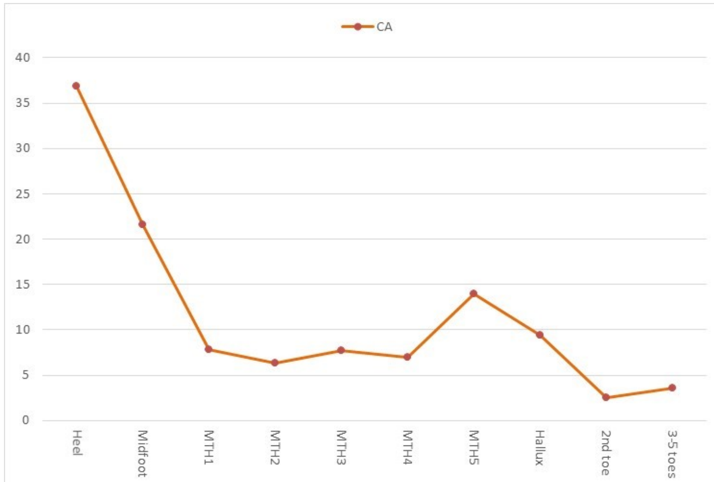


Figure 4.10: CA of combining with multiple publications

Figure 4.12 contains the results of pressure time integral parameter. It is clear that the areas of metatarsal had the two highest values. The forth metatarsal had (61.75 (3.23) kPa s) and the third metatarsal had (59.98 (3.61) kPa s). The three lowest values were under the toe areas.

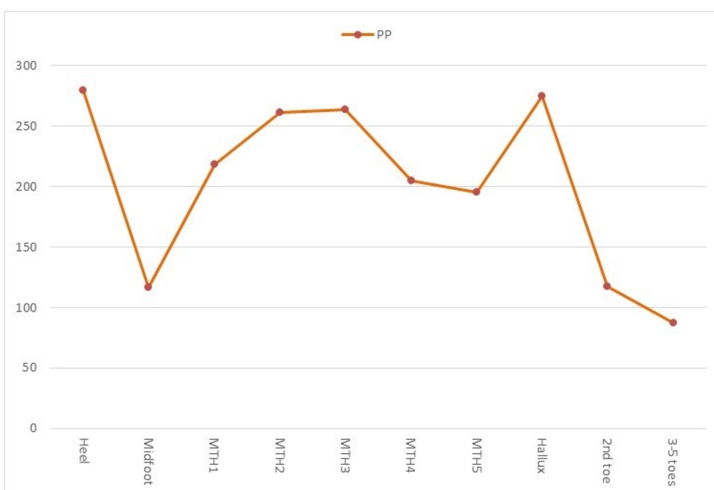


Figure 4.11: PP of combining with multiple publications

The last parameter, i.e. force time integral, was found to be highest under the heel (162.34 (5.98) N s) and midfoot (37.11 (2.77) N s). The second toe and third to fifth toe areas, in contrast, had the lowest values at 2.51 (0.30) N s and 5.40 (1.67) N s, respectively. All of the force time integral results were included in Figure 4.12.


Figure 4.12: PTI and FTI of combining with multiple publications

## 4.4 Discussion

The first aim of this study was to prove the effectiveness of the innovative alternative statistical methodology when examining the human gait of healthy young participants. It provided more accurate results in comparison with other studies which reported values of similar pressure parameters for the same 10 foot regions. It was more efficient than the other methods used in the literature for all the three cases: 1) combining with one publication by variance, 2) combining with one publication by CV and 3) combining with multiple publication by variance.

Range values for the peak pressure (kPa) in 10 regions of the foot were established by Putti et al. (2007) and Putti et al. (2008). The results of the current study in all three cases were highly consistent with these studies. Maetzler et al. (2010) provided range values for the peak pressure (kPa) for 9 foot regions. With regard to the first 8 regions, our findings were also very highly consistent with them for all of the three cases as well.

The second aim was to establish value ranges for pressure parameters, i.e. CA, MeF, PP, PTI, FTI, MF and MeA, for adults who have no clinical issues with their feet and aged between 20-60 years old by using the alternative statistical methodology. With regards to the results of combining with data from one publication, the heel and midfoot regions had the two highest values of four parameters, namely CA, MeF, FTI and MeA. The two highest values of PP and MF were in the heel and hallux regions, respectively. The third and fourth metatarsal regions had the two highest values of PTI, respectively. In addition, the metatarsal regions had the third highest value of all parameters except for PTI and MF. In contrast, seven parameters had the two lowest values in the regions of second and third-fifth toes.

## 4.5 Conclusion

This chapter analysed pressure beneath the foot parameters of healthy young adults by using the innovative alternative methodology. The underlying objectives of such a purpose were illustrating the detailed procedures for conducting human gait analysis by the proposed method and demonstrating the usefulness of the method in achieving more accurate results. The proposed methodology gave better results in both cases: combining with single and multiple publications. The range values of the pressure parameters examined in this study were also more accurate than those found using the common methodology.

Specialists in medical areas related to human gait analysis have, as a result, a better method for examining the gait of healthy young adults. They can now use the proposed methodology to perform more accurate investigations, especially for healthy young adults who have some gait issues.

# Chapter 5

# Study II: Healthy Older Adults

This chapter discusses and evaluates the efficiency of the proposed innovative statistical methodology for human gait analysis in different circumstances. The methodology is used to analyse human gait parameters of healthy older adults (aged: 60-75).

As aging can change foot functions (Bosch et al. 2009), investigating the gait of older adults is necessary. Such examination includes parameters of pressure beneath the foot, allowing experts to gain a better understanding of healthy and unhealthy conditions of the gait of older adults. This knowledge will help health practitioners diagnosing and treating older adults who have issues affecting their ability to walk normally.

As a result, the second goal of this chapter is to establish the range values of some gait parameters of older adults by using the proposed innovative statistical methodology.

## 5.1 Materials and Data

In this study, five older participants were voluntarily recruited. They were aged between 60 and 75 years old. They had no issues or pain in their lower limbs at all.

Some demographic properties were obtained from each participant: age, height and weight. The participants' mean age was 65.4 years (range: 60-70 years), mean height 168cm (range: 155-180 cm), and mean weight 74.32 kg (range: 55-94.6 kg).

### 5.1.1 Published Data

Five pressure parameters of interest for older participants were studied by McKay et al. (2017). They examined maximum force (MF), contact area (CA), peak pressure (PP), pressure time integral (PTI) and force time integral (FTI) among several other parameters. They analysed the data for the whole foot and three different regions; namely rearfoot, midfoot and forefoot.

They reported means and standard deviations for the abovementioned parameters. The data of male older adults participants were used in this study. These data are provided in Table 5.1.

They used an Emed platform to collect plantar pressure data. Participants were asked to walk at their comfortable walking speed using the two-step protocol, which requires participants to touch the platform on the second step and then continue walking for two-three steps (McKay et al. 2017).

Table 5.1: Results from McKay et al. (2017)

| Masks | MF (N) | | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 787.70 | 134.80 | 128.80 | 19.00 | 591.80 | 203.50 | 276.70 | 93.90 | 479.10 | 120.60 |
| **Rearfoot** | 496.40 | 106.70 | 39.20 | 4.40 | 356.70 | 148.30 | 101.70 | 36.70 | 147.70 | 48.60 |
| **Midfoot** | 58.10 | 51.60 | 11.90 | 7.20 | 75.90 | 63.30 | 22.90 | 20.90 | 16.20 | 18.00 |
| **Forefoot** | 765.90 | 125.50 | 77.60 | 10.10 | 576.10 | 200.00 | 219.90 | 89.80 | 315.20 | 83.50 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation

### 5.1.2 Self-captured Data

To collect data matching those collected by McKay et al. (2017), five older adults were recruited into the trials (as explained in 3.1.1). Data of maximum force (MF) N, contact area (CA) $cm^2$, peak pressure (PP) kPa, pressure time integral (PTI) kPa s and force time integral (FTI) N s were collected and analysed for the whole foot, rearfoot, midfoot and forefoot. Figure 5.1 shows the three regions of foot used in this study.

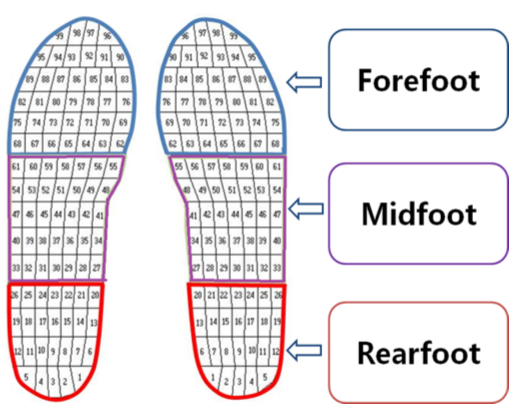


Figure 5.1: 3 Foot regions (Bae et al. 2016)

As described in Section 3.1.3, the one-step and three-steps-mean protocols were used to collect the data. Tables 5.2 and 5.3 display the results of the one-step protocol and three-steps-mean protocols, respectively. They are displayed as mean and standard deviation of the required parameters.

Table 5.2: Results of one-step protocol from healthy older participants

| Masks | MF (N) | | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 994.53 | 32.09 | 109.12 | 1.96 | 863.43 | 126.28 | 89.32 | 5.64 | 398.06 | 19.27 |
| **Rearfoot** | 687.93 | 31.06 | 33.83 | 0.81 | 495.43 | 32.77 | 55.19 | 2.65 | 126.46 | 7.24 |
| **Midfoot** | 118.32 | 11.63 | 14.44 | 1.11 | 391.03 | 88.48 | 53.44 | 21.99 | 23.26 | 5.42 |
| **Forefoot** | 964.17 | 33.11 | 58.54 | 1.29 | 779.05 | 62.21 | 66.18 | 2.67 | 254.76 | 35.80 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation

Table 5.3: Results of the three-steps-mean protocol from healthy older participants

| Masks | MF (N) | | CA (cm) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 993.96 | 31.41 | 108.51 | 2.24 | 856.37 | 97.64 | 90.11 | 3.21 | 401.54 | 12.09 |
| **Rearfoot** | 685.77 | 27.99 | 33.81 | 0.76 | 490.86 | 32.43 | 55.29 | 2.19 | 126.37 | 5.05 |
| **Midfoot** | 116.31 | 6.54 | 14.12 | 0.60 | 375.40 | 73.52 | 54.91 | 18.53 | 22.56 | 2.53 |
| **Forefoot** | 964.18 | 32.41 | 58.24 | 1.30 | 789.06 | 66.37 | 66.78 | 2.05 | 251.39 | 15.69 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation

Outlier detection and normality distribution tests were conducted with the data of the three-steps-mean protocol. Boxplot was used to detect outliers, and Shapiro-Wilks test was used to test distributions. It can be noticed from Shapiro-Wilk test results, Tables: C.1 to C.5 in Appendix C.1, that data of only one parameter out of twenty did not follow the normal distribution. The outlier detection figures in Appendix C.2, on the other hand, show that data of 14 parameters out of 20 had no outliers; see figures: C.1 to C.20. The six parameters that had outliers are: CA at the whole foot and rearfoot region, PP at the midfoot region, PTI at the rearfoot and midfoot region, FTI at the whole foot.

#### 5.1.2.1 Reliability

The intra-class correlation coefficient (ICC) was used to examine reliability. It was computed using Equation 2.5, i.e. ICC(2,k). Table 5.4 shows the results. As was demonstrated in Koo & Li (2016) and Zammit et al. (2010), we note that:

- 20 % of ICC values (4 out of 20) indicate moderate reliability.
- 65 % of ICC values (13 out of 20) indicate good reliability.
- 15 % of ICC values (3 out of 20) indicate excellent reliability.

This means the proposed methodology indicated good to excellent reliability.

Table 5.4: ICC values for older participants

| Masks | MF (N) | CA ($cm^2$) | PP (kpa) | PTI (kPa s) | FTI (N s) |
|---|---|---|---|---|---|
| Whole foot | 0.80 | 0.63 | 0.80 | 0.94 | 0.80 |
| Reafoot | 0.81 | 0.71 | 0.83 | 0.82 | 0.75 |
| Midfoot | 0.50 | 0.82 | 0.94 | 0.79 | 0.95 |
| Forefoot | 0.79 | 0.82 | 0.73 | 0.86 | 0.87 |

## 5.2 Innovative Statistical Methodology for Older Participants

The suggested alternative statistical methodology can be applied using single and multiple publications. Therefore, both cases are included in the following sections.

### 5.2.1 Single publication

To choose the highly accurate self-captured data in the case of combining with a single publication, the results of one-step and three-steps-mean protocols were compared to determine the protocol with higher accuracy. A quick look at the SD's in Tables 5.2 and 5.3, reveals that the three-steps-mean protocol had greater accuracy than the one-step protocol. Therefore, the results of Tables 5.3 and 5.1 were used in all procedures of the alternative statistical methodology.

The first phase assigns weights for each measurement of the self-captured trials and single publication by using Equation 3.1, i.e. assigning weights by variance. Tables 5.5 and 5.6 show the weighting values of the self-captured and single published data, respectively.

After calculating the weights and other required values, Equations 3.6 and 3.7 were used to calculate the weighted mean and standard error. The final results of the alternative statistical methodology by using a single publication are displayed in Table 5.7.

Table 5.5: Weighting values for the three-steps-mean protocol measurements for healthy older participants

| Masks | MF (N) | | | | | CA (cm$^2$) | | | | | PP (kPa) | | | | | PTI (kPa s) | | | | | FTI (N s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 993.96 | 31.41 | 986.58 | 0.001 | 1.01 | 108.51 | 2.24 | 5.00 | 0.20 | 21.70 | 856.37 | 97.64 | 9533.67 | 0.0001 | 0.09 | 90.11 | 3.21 | 10.31 | 0.10 | 8.74 | 401.54 | 12.09 | 146.16 | 0.01 | 2.75 |
| **Rearfoot** | 685.77 | 27.99 | 783.53 | 0.001 | 0.88 | 33.81 | 0.76 | 0.58 | 1.72 | 58.03 | 490.86 | 32.43 | 1051.70 | 0.0010 | 0.47 | 55.29 | 2.19 | 4.78 | 0.21 | 11.56 | 126.37 | 5.05 | 25.49 | 0.04 | 4.96 |
| **Midfoot** | 116.31 | 6.54 | 42.83 | 0.023 | 2.72 | 14.12 | 0.60 | 0.37 | 2.74 | 38.63 | 375.40 | 73.52 | 5405.48 | 0.0002 | 0.07 | 54.91 | 18.53 | 343.42 | 0.003 | 0.16 | 22.56 | 2.53 | 6.40 | 0.16 | 3.52 |
| **Forefoot** | 964.18 | 32.41 | 1050.18 | 0.001 | 0.92 | 58.24 | 1.30 | 1.69 | 0.59 | 34.48 | 789.06 | 66.37 | 4405.53 | 0.0002 | 0.18 | 66.78 | 2.05 | 4.22 | 0.24 | 15.81 | 251.39 | 15.69 | 246.21 | 0.00 | 1.02 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation; var: variance; wi: weight

Table 5.6: Weighting values for measurements from McKay et al. (2017)

| Masks | MF (N) | | | | | CA (cm$^2$) | | | | | PP (kPa) | | | | | PTI (kPa s) | | | | | FTI (N s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** | **mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 787.70 | 134.80 | 18171.04 | 0.0001 | 0.04 | 128.80 | 19.00 | 361.00 | 0.003 | 0.36 | 591.80 | 203.50 | 41412.25 | 0.00002 | 0.01 | 276.70 | 93.90 | 8817.21 | 0.0001 | 0.03 | 479.10 | 120.60 | 14544.36 | 0.0001 | 0.03 |
| **Rearfoot** | 496.40 | 106.70 | 11384.89 | 0.0001 | 0.04 | 39.20 | 4.40 | 19.36 | 0.05 | 2.02 | 356.70 | 148.30 | 21992.89 | 0.00005 | 0.02 | 101.70 | 36.70 | 1346.89 | 0.0007 | 0.08 | 147.70 | 48.60 | 2361.96 | 0.0004 | 0.06 |
| **Midfoot** | 58.10 | 51.60 | 2662.56 | 0.0004 | 0.02 | 11.90 | 7.20 | 51.84 | 0.02 | 0.23 | 75.90 | 63.30 | 4006.89 | 0.00025 | 0.02 | 22.90 | 20.90 | 436.81 | 0.0023 | 0.05 | 16.20 | 18.00 | 324.00 | 0.0031 | 0.05 |
| **Forefoot** | 765.90 | 125.50 | 15750.25 | 0.0001 | 0.05 | 77.60 | 10.10 | 102.01 | 0.01 | 0.76 | 576.10 | 200.00 | 40000.00 | 0.00003 | 0.01 | 219.90 | 89.80 | 8064.04 | 0.0001 | 0.03 | 315.20 | 83.50 | 6972.25 | 0.0001 | 0.05 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; SD: standard deviation; var: variance; wi: weight

These results show that the alternative statistical methodology achieved more accurate results than that of McKay et al. (2017), i.e. Table 5.1. It can be seen that all parameters (20 out of 20) had less SE's when analysed by the proposed methodology.

Table 5.7: Results of alternative statistical methodology for healthy older participants (single publication)

| Masks | MF (N) | | CA ($cm^2$) | | PP (kPa) | | PTI (kPa s) | | FTI (N s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** | **M** | **SE** |
| **Whole foot** | 983.33 | 30.59 | 108.79 | 2.22 | 806.86 | 88.03 | 90.33 | 3.21 | 402.31 | 12.03 |
| **Rearfoot** | 673.57 | 27.08 | 33.97 | 0.75 | 484.74 | 31.68 | 55.45 | 2.18 | 126.60 | 5.02 |
| **Midfoot** | 115.39 | 6.49 | 14.11 | 0.60 | 203.40 | 47.97 | 40.82 | 13.87 | 22.43 | 2.51 |
| **Forefoot** | 951.79 | 31.38 | 58.55 | 1.29 | 767.94 | 63.00 | 66.86 | 2.05 | 253.56 | 15.42 |

MF: maximum force; CA: contact area; PP: peak pressure; PTI: pressure time integral; FTI: force time integral; M: weighted mean; SE: standard error

### 5.2.2 Multiple publications

Another way to prove the efficiency of the proposed methodology is to use it in the case of combining data from self-captured trials and more than one publications. For that purpose, we need to find multiple publications studying similar pressure parameters for the same foot regions. Two articles were found in the literature, namely Zammit et al. (2008) and Menz & Morris (2006). Both of these publications reported maximum force (MF) and peak pressure (PP) for the same foot regions: heel, midfoot, first metatarsal, second metatarsal, third to fifth metatarsal, hallux and lesser toes. These foot regions are shown in Figure 5.2.

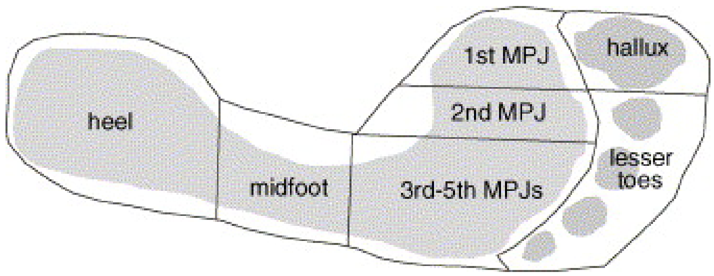


Figure 5.2: 7-foot regions (Menz & Morris 2006)

The mean and standard deviation of the parameters from Zammit et al. (2008) and Menz & Morris (2006) are presented in Tables 5.8 and 5.9, respectively.

Table 5.8: Results from Zammit et al. (2008)

| Masks | MF (kg) | | PP (kg/cm$^2$) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 35.60 | 9.00 | 2.10 | 0.40 |
| **Midfoot** | 12.50 | 7.00 | 0.80 | 0.30 |
| **1st MTH** | 14.30 | 5.30 | 1.70 | 0.50 |
| **2nd MTH** | 16.30 | 4.40 | 2.30 | 0.40 |
| **3rd-5th MTH** | 15.50 | 5.80 | 1.60 | 0.40 |
| **Hallux** | 5.90 | 1.70 | 1.30 | 0.30 |
| **Lesser toes** | 3.50 | 1.40 | 0.70 | 0.20 |

MF: maximum force; PP: peak pressure; SD: standard deviation; MTH: metatarsal head

Table 5.9: Results from Menz & Morris (2006)

| Masks | MF (kg) | | PP (kg/cm$^2$) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 34.23 | 8.60 | 1.99 | 0.48 |
| **Midfoot** | 9.60 | 6.20 | 0.69 | 0.39 |
| **1st MTH** | 15.37 | 5.36 | 1.65 | 0.47 |
| **2nd MTH** | 14.62 | 4.29 | 2.09 | 0.53 |
| **3rd-5th MTH** | 12.03 | 5.21 | 1.35 | 0.45 |
| **Hallux** | 5.52 | 2.76 | 1.21 | 0.46 |
| **Lesser toes** | 3.88 | 2.16 | 0.71 | 0.28 |

MF: maximum force; PP: peak pressure; SD: standard deviation; MTH: metatarsal head

Now, we need data from self-captured trials. As the data mentioned in Section 5.1.2 were captured from different foot regions than those in Zammit et al. (2008) and Menz & Morris (2006), new data were obtained from the same above mentioned trials of the same five older participants. These data were for maximum force (MF)and peak pressure (PP) but in different units to match the published data. The maximum force was measured by kilogram, whereas the peak pressure was measured by kilogram per square centimetre. These two parameters were calculated from the abovementioned seven regions of the foot, i.e. heel, midfoot, first metatarsal, second metatarsal, third to fifth metatarsal, hallux and lesser toes. Only the three-steps-mean protocol was used as it proved to have more accurate results in Section 5.2.1.Thus, Table 5.10 presents the results in the format of mean and standard deviation of the self-captured trials for the purpose of combining with multiple publications.

Table 5.10: Three-steps-mean protocol results

| Masks | MF (kg) | | PP ($kg/cm^2$) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| **Heel** | 71.37 | 2.85 | 5.01 | 0.33 |
| **Midfoot** | 11.09 | 0.76 | 3.75 | 0.78 |
| **1st MTH** | 23.88 | 1.54 | 4.45 | 0.50 |
| **2nd MTH** | 19.16 | 1.05 | 5.79 | 0.67 |
| **3rd-5th MTH** | 38.42 | 2.71 | 5.54 | 0.37 |
| **Hallux** | 17.71 | 1.12 | 6.25 | 0.57 |
| **Lesser toes** | 3.74 | 0.96 | 1.40 | 0.18 |

MF: maximum force; PP: peak pressure; SD: standard deviation; MTH: metatarsal head

After obtaining all the required data, Equation 3.1 was used to assign weight by variance for each measurement. The weighting values for the self-captured data, Zammit's data and Menz's data are displayed in Tables 5.11, 5.12 and 5.13, respectively.

Table 5.11: Weighting values for the three-steps-mean protocol of older participants (for combining multiple publications)

| Masks | MF (kg) | | | | | PP ($kg/cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 71.37 | 2.85 | 8.13 | 0.12 | 8.78 | 5.01 | 0.33 | 0.11 | 9.03 | 45.23 |
| **Midfoot** | 11.09 | 0.76 | 0.58 | 1.72 | 19.11 | 3.75 | 0.78 | 0.61 | 1.64 | 6.17 |
| **1st MTH** | 23.88 | 1.54 | 2.37 | 0.42 | 10.08 | 4.45 | 0.50 | 0.25 | 4.08 | 18.15 |
| **2nd MTH** | 19.16 | 1.05 | 1.10 | 0.91 | 17.38 | 5.79 | 0.67 | 0.45 | 2.23 | 12.90 |
| **3rd-5th MTH** | 38.42 | 2.71 | 7.36 | 0.14 | 5.22 | 5.54 | 0.37 | 0.13 | 7.47 | 41.36 |
| **Hallux** | 17.71 | 1.12 | 1.25 | 0.80 | 14.21 | 6.25 | 0.57 | 0.33 | 3.07 | 19.18 |
| **Lesser toes** | 3.74 | 0.96 | 0.91 | 1.09 | 4.10 | 1.40 | 0.18 | 0.03 | 31.08 | 43.56 |

MF: maximum force; PP: peak pressure; SD: standard deviation; var: variance; wi: weight; MTH: metatarsal head

Table 5.12: Weighting values for Zammit's data

| Masks | MF (kg) | | | | | PP ($kg/cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 35.60 | 9.00 | 81.00 | 0.01 | 0.44 | 2.10 | 0.40 | 0.16 | 6.25 | 13.13 |
| **Midfoot** | 12.50 | 7.00 | 49.00 | 0.02 | 0.26 | 0.80 | 0.30 | 0.09 | 11.11 | 8.89 |
| **1st MTH** | 14.30 | 5.30 | 28.09 | 0.04 | 0.51 | 1.70 | 0.50 | 0.25 | 4.00 | 6.80 |
| **2nd MTH** | 16.30 | 4.40 | 19.36 | 0.05 | 0.84 | 2.30 | 0.40 | 0.16 | 6.25 | 14.38 |
| **3rd-5th MTH** | 15.50 | 5.80 | 33.64 | 0.03 | 0.46 | 1.60 | 0.40 | 0.16 | 6.25 | 10.00 |
| **Hallux** | 5.90 | 1.70 | 2.89 | 0.35 | 2.04 | 1.30 | 0.30 | 0.09 | 11.11 | 14.44 |
| **Lesser toes** | 3.50 | 1.40 | 1.96 | 0.51 | 1.79 | 0.70 | 0.20 | 0.04 | 25.00 | 17.50 |

MF: maximum force; PP: peak pressure; SD: standard deviation; var: variance; wi: weight; MTH: metatarsal head

Table 5.13: Weighting values for Menz's data

| Masks | MF (kg) | | | | | PP ($kg/cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Heel** | 34.23 | 8.60 | 73.96 | 0.01 | 0.46 | 1.99 | 0.48 | 0.23 | 4.34 | 8.64 |
| **Midfoot** | 9.60 | 6.20 | 38.44 | 0.03 | 0.25 | 0.69 | 0.39 | 0.15 | 6.57 | 4.54 |
| **1st MTH** | 15.37 | 5.36 | 28.73 | 0.03 | 0.53 | 1.65 | 0.47 | 0.22 | 4.53 | 7.47 |
| **2nd MTH** | 14.62 | 4.29 | 18.40 | 0.05 | 0.79 | 2.09 | 0.53 | 0.28 | 3.56 | 7.44 |
| **3rd-5th MTH** | 12.03 | 5.21 | 27.14 | 0.04 | 0.44 | 1.35 | 0.45 | 0.20 | 4.94 | 6.67 |
| **Hallux** | 5.52 | 2.76 | 7.62 | 0.13 | 0.72 | 1.21 | 0.46 | 0.21 | 4.73 | 5.72 |
| **Lesser toes** | 3.88 | 2.16 | 4.67 | 0.21 | 0.83 | 0.71 | 0.28 | 0.08 | 12.76 | 9.06 |

MF: maximum force; PP: peak pressure; SD: standard deviation; var: variance; wi: weight; MTH: metatarsal head

The final step in the alternative statistical methodology is using Equations 3.6 and 3.7 to calculate the weighted mean and standard error. The results of combining data from self-captured trials and multiple publications by using the alternative statistical methodology are shown in Table 5.14.

Table 5.14: Alternative statistical methodology results of older participants (multiple publications)

| Masks | MF (kg) | | PP (kg/cm$^2$) | |
|---|---|---|---|---|
| | **Mean** | **SE** | **Mean** | **SE** |
| **Heel** | 65.03 | 2.59 | 3.41 | 0.23 |
| **Midfoot** | 11.09 | 0.75 | 1.01 | 0.23 |
| **1st MTH** | 22.58 | 1.43 | 2.57 | 0.28 |
| **2nd MTH** | 18.77 | 0.99 | 2.88 | 0.29 |
| **3rd-5th MTH** | 30.25 | 2.22 | 3.11 | 0.23 |
| **Hallux** | 13.27 | 0.88 | 2.08 | 0.23 |
| **Lesser toes** | 3.69 | 0.74 | 1.02 | 0.12 |

MF: maximum force; PP: peak pressure; SD: standard deviation; MTH: metatarsal head

## 5.3 Results

The results of the innovative statistical methodology in both cases, i.e. single and multiple publications, are presented in detail throughout this section.

### 5.3.1 Single publication

Table 5.7 shows the results of applying the proposed alternative statistical methodology to analyse gait parameters of healthy older adult participants after combining self-captured data with those of a single publication. These results indicated that, as shown in Figure 5.3, the whole foot had the biggest value of maximum force at (983.33 (30.59) N). The forefoot region had (951.79 (31.38) N), followed by the rearfoot (673.57 (27.08) N) and the midfoot (115.39 (6.49) N), respectively.

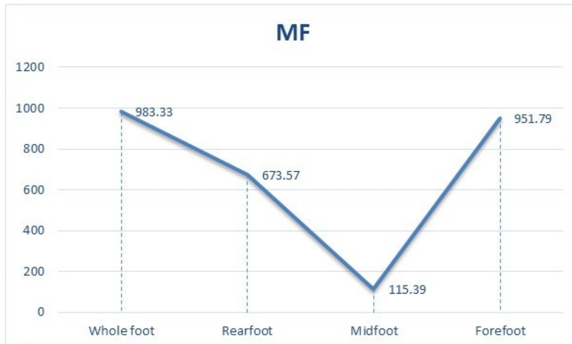


Figure 5.3: MF results of alternative methodology (single publication)

The largest contact area was under the whole foot at (108.79 (2.22) $cm^2$), while the second largest contact area was under the region of forefoot at (58.55 (1.29) $cm^2$). In contrast, the smallest values of the contact area parameters were under the rearfoot and midfoot at 33.97 (0.75) $cm^2$ and 14.11 (0.60) $cm^2$, respectively. The results of the contact area are shown in Figure 5.4.

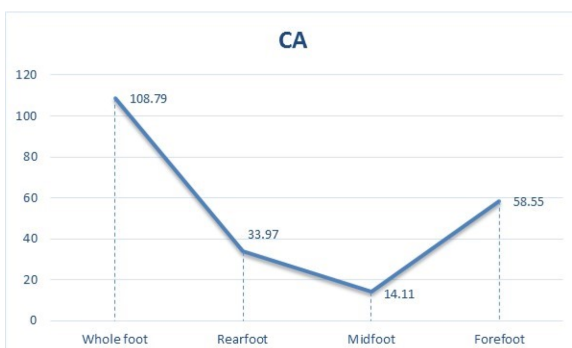


Figure 5.4: CA results of alternative methodology (single publication)

With regards to the peak pressure parameters, Figure 5.5 shows that the whole foot had the largest value at 806.86 (88.03) kPa. The second and third largest values of peak pressure were under the forefoot (767.94 (63) kPa) and the rearfoot (484.74

(31.68) kPa). The lowest peak pressure was under the midfoot region at (203.40 (47.97) kPa).

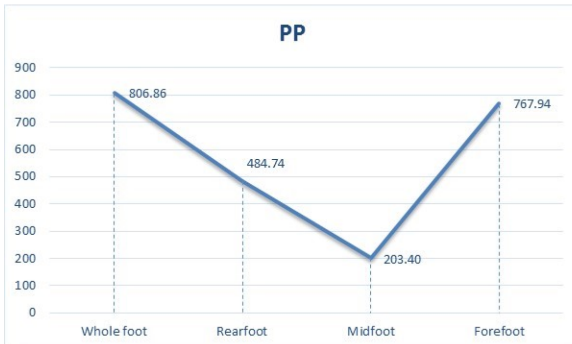


Figure 5.5: PP results of alternative methodology (single publication)

Moreover, the biggest values of the pressure time integral parameter as appears in Figure 5.6 was under the whole foot and the forefoot region at 90.33 (3.21) kPa s and 66.86 (2.05) kPa s, respectively. The lowest value was under the midfoot at 40.82 (13.87) kPa s.

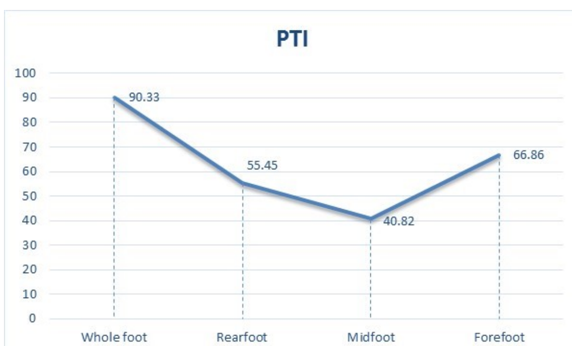


Figure 5.6: PTI results of alternative methodology (single publication)

Lastly, the force time integral was the biggest under the whole foot at 402.31 (12.03) N s. This was followed by the forefoot (253.56 (15.42) N s) and rearfoot (126.6 (5.02) N s). While, the smallest value was under the midfoot region at (22.43 (2.51) N s). These results are displayed in Figure 5.7.

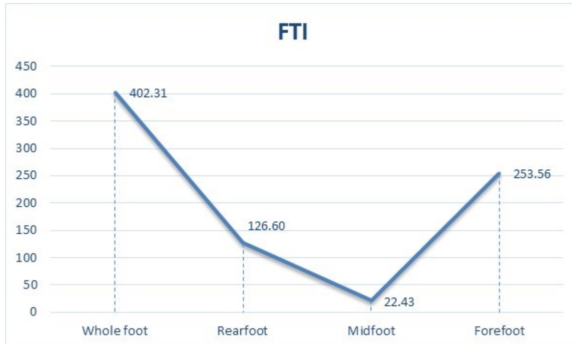


Figure 5.7: FTI results of alternative methodology (single publication)

## 5.3.2 Multiple publications

In terms of combining with multiple publications, the proposed alternative statistical methodology gave the following results.

As shown in Table 5.14 and Figure 5.8, the heel region had the biggest value of the maximum force at: (65.03 (2.59) kg). While the metatarsal regions had the second, third and fourth biggest values at: 3nd-5th MTH (30.25 (2.22) kg), 1st MTH (22.58 (1.43) kg) and 2nd MTH (18.77 (0.99) kg). In addition, the last three biggest values were under the regions of the hallux, midfoot and lesser toes at 13.27 (0.88) kg, 11.09 (0.75) kg and 3.69 (0.74), respectively.

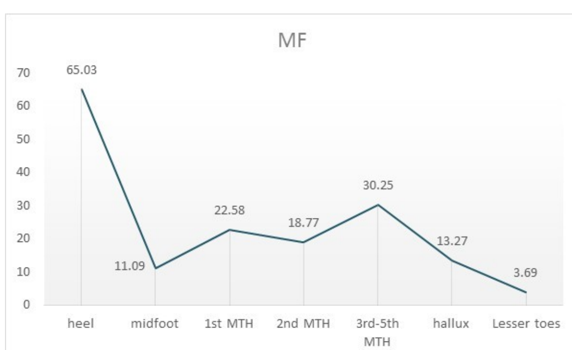


Figure 5.8: MF results of alternative methodology (multiple publications)

The results of the peak pressure parameter showed that the largest peak pressure was under the heel region at (3.41 (0.23) kg/cm$^2$). This was followed by the regions of 3rd - 5th MTH (3.11 (0.23) kg/cm$^2$), 2nd MTH (2.88 (0.29) kg/cm$^2$) and 1st MTH (2.57 (0.28) kg/cm$^2$). The lowest peak pressure was under the region of midfoot at (1.01 (0.23) kg/cm$^2$). These results are presented in Table 5.14 and Figure 5.9.

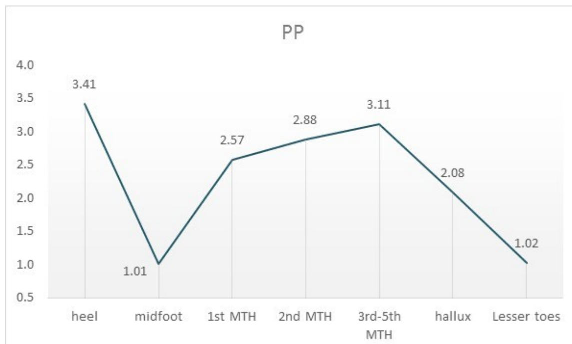


Figure 5.9: PP results of alternative methodology (multiple publications)

## 5.4 Discussion

The developed method was used to analyse parameters of the pressure beneath the foot of a new group of participants, i.e. healthy older adults. It gave more accurate results across all the parameters studied in both cases, i.e. combining with single and multiple publications.

This study established the range of values of pressure beneath the foot parameters, as follows:

1. In the case of combining with a single publication
   Range values of maximum force (MF), contact area (CA), peak pressure (PP), pressure time integral (PTI) and force time integral (FTI) for the whole foot, rearfoot, midfoot and forefoot were established. The findings were in agreement

with those of McKay et al. (2017). Both studies found that the whole foot had the biggest values of all the mentioned parameters, which was followed by the region of the forefoot, rearfoot and midfoot, respectively.

2. In the case of combining with multiple publications

   Applying the proposed methodology by combining data from self-captured trials and multiple publications led to establishing a range of values of maximum force (MF) and peak pressure (PP) for different foot regions, i.e. heel, midfoot, 1st MTH, 2nd MTH, 3rd - 5th MTH, hallux and lesser toes. The findings were in agreement with those of Zammit et al. (2008) and Menz & Morris (2006). With respect to the parameter of maximum force, all three studies found that the heel region had the highest value. The metatarsal regions had the second, third and fourth highest values. While, the lesser toes region had the lowest value. These three studies found the third and fourth biggest values of the peak pressure parameter were under the metatarsal regions. In addition, our study and Menz & Morris (2006) found that the fifth, sixth and seventh biggest values of the peak pressure were under the hallux, lesser toes and heel, in decreasing order.

## 5.5 Conclusion

Applying the innovative statistical methodology to analyse gait parameters of healthy older adult participants was the main aim of this chapter. This includes proving the accuracy of the methodology, showing it to be the most efficient of the methodologies used and establishing range values of the parameters studied. The results of the current study proved the efficiency of the proposed alternative statistical methodology in the analysis of gait parameters of healthy older adult participants. These results also showed that this method helps to improve the outcomes of the analysis of human gait. It gave better results in the cases of using single and multiple publications in the combining process.

Therefore, this chapter introduced a more efficient methodology to analyse gait characteristics of healthy older adults. It is a novel approach that can be used by human gait clinicians to reach better diagnoses and treatments for those older individuals who suffer from gait abnormalities.

# Chapter 6

# Study III: Obese Adults

As this thesis has a very particular interest in proving the effectiveness of the innovative statistical methodology for analysing human gait, another group of participants was targeted. The pressure parameters of a group of obese adults are analysed with the innovative statistical methodology developed. In addition, this chapter aims to establish range values of such parameters for obese participants by using the proposed methodology.

Anandacoomarasamy et al. (2008) and Butterworth et al. (2015) pointed out that there is a relationship between obesity and foot pain. Butterworth et al. (2012) found that foot pain is strongly associated with increased body mass index, particularly chronic pain in the plantar heel region in a non-athletic population and non-specific foot pain in the genal population. In addition, Hills et al. (2001) reported a link between the obesity, increased force and pressure beneath the foot. Moreover, obesity is one of the major health problems of increasing prevalence in both developing and developed countries (Gregor & Hotamisligil 2011). Therefore, it is very important to study gait parameters for obese adults and establish value ranges for them.

## 6.1 Materials and Data Collecting

Five obese volunteers were engaged in this study. They were classified as obese using body mass index (BMI). According to a report by the World Health Organisation, any person with a BMI $\geq$ 30 kg/m$^2$ is considered obese (Organization 2000). After recording the weight and height of each participant, all were found to have a BMI $\geq$ 30 kg/m$^2$. They also had a clear history of no particular health conditions that could impact their ability to walk normally.

In addition to the weight and height, the age of each participant was recorded. The average age, weight and height were 39.4 years old (range 31-50 years), 105.36 kg (range 92.8-122 kg) and 174 cm (range 163-185 cm), respectively.

Participants were required to walk along a walkway, 10-metres long, in a laboratory setting at a self-chosen speed. They were given appropriate sized shoes with 3000E F-Scan in-shoe sensors inserted inside them to wear. The whole trials were conducted during two sessions with a one week space between them. Each session included twelve trials. Data for the sixth, seventh and eighth steps were analysed.

### 6.1.1 Data from published works

With respect to the targeted pressure parameters, a published article was found: Butterworth et al. (2015). It reported the values of mean and standard deviation of three parameters of interest. The three parameters, i.e. contact area (CA), maximum force (MF) and peak pressure (PP), were studied for six different regions of the foot: whole foot, heel, midfoot, forefoot, hallux and toes.

Data of sixty-eight volunteers from a previous study (Tanamas et al. 2012) were used in this study to evaluate plantar patterns in obese and non-obese participants

(Butterworth et al. 2015). Body mass index (BMI) was used to determine whether each person was obese or not. The MatScan system was used to collect pressure data, and the platform was positioned in the centre of a flat walkway. Participants were asked to walk across the platform hitting it with their right foot. The results in the form of mean and standard deviation are presented in Table 6.1.

Table 6.1: Results from Butterworth et al. (2015)

| Masks | MF (kg) | | CA ($cm^2$) | | PP ($kg/cm^2$) | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 81.30 | 21.10 | 116.60 | 16.00 | 2.70 | 0.30 |
| **Heel** | 40.40 | 11.90 | 30.30 | 4.70 | 2.20 | 0.40 |
| **Midfoot** | 20.80 | 12.00 | 30.70 | 8.00 | 1.30 | 0.50 |
| **Forefoot** | 56.90 | 16.90 | 49.10 | 5.60 | 2.70 | 0.30 |
| **Hallux** | 10.00 | 6.60 | 10.20 | 1.60 | 1.70 | 0.40 |
| **Toes** | 5.10 | 3.30 | 10.20 | 2.50 | 0.90 | 0.30 |

MF: maximum force; CA: contact area; PP: peak pressure; SD: standard deviation

### 6.1.2 Data from self-captured trials

Following Butterworth et al. (2015), three pressure beneath the foot parameters were collected from six different regions of the foot for the five participants. The pressure parameters are: maximum force (MF) kg, contact area (CA) $cm^2$ and peak pressure (PP) $kg/cm^2$. These parameters were calculated for the regions of: the whole foot, heel, midfoot, forefoot, hallux and toes. Figure 6.1 shows these regions.

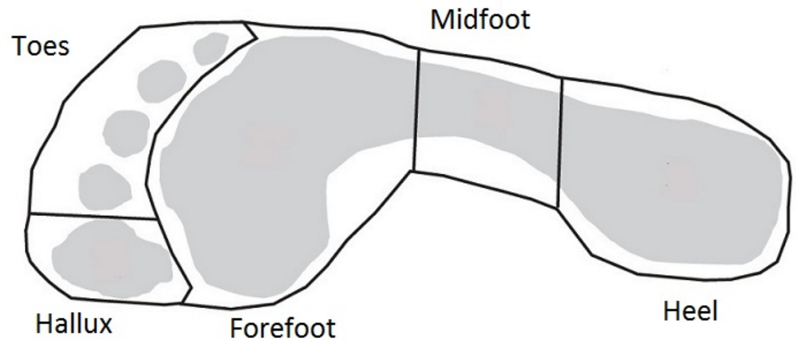


Figure 6.1: 5 foot regions (Butterworth et al. 2015)

After recording data from the gait trials, the mean and standard deviation were calculated for both proposed protocols (see Section 3.1.3). The seventh step was used for the one-step protocol, and the sixth, seventh and eighth step were used for the three-steps-mean protocol. Tables 6.2 and 6.3 display the results of the three-steps-mean and one-step protocols, respectively.

Table 6.2: Results of the three-steps-mean protocol from obese participants

| Masks | MF (kg) | | CA ($cm^2$) | | PP ($kg/cm^2$) | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 133.67 | 4.75 | 151.03 | 3.16 | 4.73 | 0.33 |
| **Heel** | 93.02 | 4.30 | 43.00 | 0.37 | 4.26 | 0.24 |
| **Midfoot** | 23.37 | 2.40 | 25.54 | 1.37 | 2.05 | 0.20 |
| **Forefoot** | 114.65 | 5.42 | 55.90 | 0.30 | 4.58 | 0.30 |
| **Hallux** | 18.86 | 1.67 | 10.75 | 0.24 | 3.35 | 0.30 |
| **Toes** | 3.21 | 0.98 | 5.58 | 1.38 | 0.92 | 0.16 |

MF: maximum force; CA: contact area; PP: peak pressure; SD: standard deviation

Table 6.3: Results of one-step protocol from obese participants

| Masks | MF (kg) | | CA ($cm^2$) | | PP ($kg/cm^2$) | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 133.63 | 4.76 | 151.08 | 3.32 | 4.73 | 0.31 |
| **Heel** | 93.23 | 4.80 | 43.09 | 0.38 | 4.27 | 0.27 |
| **Midfoot** | 23.11 | 2.67 | 25.59 | 1.76 | 2.02 | 0.25 |
| **Forefoot** | 114.51 | 5.56 | 55.86 | 0.35 | 4.57 | 0.32 |
| **Hallux** | 19.17 | 2.10 | 10.76 | 0.39 | 3.36 | 0.37 |
| **Toes** | 3.23 | 1.21 | 5.44 | 1.58 | 0.92 | 0.20 |

MF: maximum force; CA: contact area; PP: peak pressure; SD: standard deviation

The three-steps-mean protocol data were examined for outliers and distribution. Normality was investigated using the Shapiro-Wilks test. Tables: D.1 to D.3 show that the data for all 18 studied parameters were normally distributed (see Appendix D.1). Appendix D.2 provides 18 figures, Figure D.1 to Figure D.18, to present the results of the outlier detection. From these figures it can be seen that, 15 out of 18 (83.33%) parameters had no outliers (see Appendix D.2).

### 6.1.3 Reliability

Reliability was evaluated by calculating the Intra-class correlation coefficient (ICC), in particular ICC(2,k) using Equation 2.5. The results of ICC calculation for all the parameters studied are displayed in Table 6.4. Interpretation of the ICCs is organised according to Koo & Li (2016) and Zammit et al. (2010). Therefore, by reviewing Table 6.4, we can see that:

- 16.66 % of ICC values (3 out of 18) indicate moderate reliability.
- 55.55 % of ICC values (10 out of 18) indicate good reliability.
- 37.77 % of ICC values (5 out of 18) indicate excellent reliability.

Consequently, the proposed alternative statistical methodology showed good to excellent reliability in general.

Table 6.4: ICC values for obese participants

| Masks | **MF (kg)** | **CA ($cm^2$)** | **PP ($kg/cm^2$)** |
|---|---|---|---|
| **Whole foot** | 0.860 | 0.720 | 0.763 |
| **Heel** | 0.850 | 0.862 | 0.771 |
| **Midfoot** | 0.700 | 0.922 | 0.878 |
| **Forefoot** | 0.900 | 0.911 | 0.913 |
| **Hallux** | 0.630 | 0.812 | 0.815 |
| **Toes** | 0.904 | 0.892 | 0.921 |

MF: maximum force; CA: contact area; PP: peak pressure

## 6.2 Innovative Statistical Methodology for Obese Participants

Before combining the self-captured data with the published data, it must be decided which one of the two proposed protocols gives more accurate results. Therefore, the results of Tables 6.2 and 6.3 must be compared. It can be noticed that the three-steps-mean protocol had lower values of standard deviation than those of the one-step protocol for 17 out of 18 (94.5%) parameters.

Accordingly, the results of the three-steps-mean protocol was used in the combination procedures of the alternative statistical methodology for the obese adults group. The higher accuracy of the three-steps-mean protocol over the common protocol used in Butterworth et al. (2015) can be revealed by making a quick comparison between the results of these two protocols. By comparing Tables 6.2 and 6.1, we can observe that 17 values out of 18 of the standard deviation of the three-steps-mean protocol were lower than all of those of Butterworth et al. (2015), i.e. 94.5% of the parameters were more accurate.

### 6.2.1 One publication for combining procedures by variance

After determining the more accurate self-captured data, we start by combining with one publication. The results of Butterworth et al. (2015) were used. Thus, Tables 6.1 and 6.2 were used to assign weight for each parameter using variance, i.e. by using Equation 3.1. The results of that process are presented in Tables 6.5 and 6.6.

Table 6.5: Weighting values for the three-steps-mean protocol for obese participants by variance

| Masks | MF (kg) | | | | | CA ($cm^2$) | | | | | PP ($kg/cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 133.67 | 4.75 | 22.59 | 0.04 | 5.92 | 151.03 | 3.16 | 10.01 | 0.10 | 15.08 | 4.73 | 0.33 | 0.11 | 8.99 | 42.53 |
| **Heel** | 93.02 | 4.30 | 18.51 | 0.05 | 5.02 | 43.00 | 0.37 | 0.14 | 7.17 | 308.38 | 4.26 | 0.24 | 0.06 | 17.27 | 73.60 |
| **Midfoot** | 23.37 | 2.40 | 5.77 | 0.17 | 4.05 | 25.54 | 1.37 | 1.89 | 0.53 | 13.55 | 2.05 | 0.20 | 0.04 | 26.25 | 53.78 |
| **Forefoot** | 114.65 | 5.42 | 29.43 | 0.03 | 3.90 | 55.90 | 0.30 | 0.09 | 11.48 | 641.69 | 4.58 | 0.30 | 0.09 | 10.89 | 49.87 |
| **Hallux** | 18.86 | 1.67 | 2.78 | 0.36 | 6.78 | 10.75 | 0.24 | 0.06 | 17.96 | 193.11 | 3.35 | 0.30 | 0.09 | 11.03 | 36.93 |
| **Toes** | 3.21 | 0.98 | 0.97 | 1.03 | 3.30 | 5.58 | 1.38 | 1.90 | 0.53 | 2.94 | 0.92 | 0.16 | 0.03 | 37.92 | 34.99 |

MF: maximum force; CA: contact area; PP: peak pressure; SD: standard deviation; var: variance; wi: weight

Table 6.6: Weighting values for Butterworth's data by variance

| Masks | MF (kg) | | | | | CA ($cm^2$) | | | | | PP ($kg/cm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 81.30 | 21.10 | 445.21 | 0.00 | 0.18 | 116.60 | 16.00 | 256.00 | 0.00 | 0.46 | 2.70 | 0.30 | 0.09 | 11.11 | 30.00 |
| **Heel** | 40.40 | 11.90 | 141.61 | 0.01 | 0.29 | 30.30 | 4.70 | 22.09 | 0.05 | 1.37 | 2.20 | 0.40 | 0.16 | 6.25 | 13.75 |
| **Midfoot** | 20.80 | 12.00 | 144.00 | 0.01 | 0.14 | 30.70 | 8.00 | 64.00 | 0.02 | 0.48 | 1.30 | 0.50 | 0.25 | 4.00 | 5.20 |
| **Forefoot** | 56.90 | 16.90 | 285.61 | 0.004 | 0.20 | 49.10 | 5.60 | 31.36 | 0.03 | 1.57 | 2.70 | 0.30 | 0.09 | 11.11 | 30.00 |
| **Hallux** | 10.00 | 6.60 | 43.56 | 0.02 | 0.23 | 10.20 | 1.60 | 2.56 | 0.39 | 3.98 | 1.70 | 0.40 | 0.16 | 6.25 | 10.63 |
| **Toes** | 5.10 | 3.30 | 10.89 | 0.09 | 0.47 | 10.20 | 2.50 | 6.25 | 0.16 | 1.63 | 0.90 | 0.30 | 0.09 | 11.11 | 10.00 |

MF: maximum force; CA: contact area; PP: peak pressure; SD: standard deviation; var: variance; wi: weight

The last step of the alternative statistical methodology is computing the weighted means and standard errors. Equations 3.6 and 3.7, and Tables 6.5 and 6.6 were used for this purpose, and the results are displayed in Table 6.7.

Table 6.7: Results of alternative statistical methodology by variance for obese participants (combined with one publication)

| Masks | MF (kg) | | CA ($cm^2$) | | PP ($kg/cm^2$) | |
|---|---|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** | **M** | **SE** |
| **Whole foot** | 131.14 | 4.64 | 149.74 | 3.10 | 3.61 | 0.22 |
| **Heel** | 86.93 | 4.05 | 42.92 | 0.37 | 3.71 | 0.21 |
| **Midfoot** | 23.27 | 2.35 | 25.69 | 1.35 | 1.95 | 0.18 |
| **Forefoot** | 109.26 | 5.17 | 55.88 | 0.29 | 3.63 | 0.21 |
| **Hallux** | 18.33 | 1.62 | 10.74 | 0.23 | 2.75 | 0.24 |
| **Toes** | 3.36 | 0.94 | 6.66 | 1.21 | 0.92 | 0.14 |

MF: maximum force; CA: contact area; PP: peak pressure; M: weighted mean; SE: standard error

By comparing Tables 6.1 and 6.7, we can see that, once again, the alternative statistical methodology gave more accurate results for a different group of participants, i.e. obese adults, and for different foot regions, where 18 out of the 18 (100%) parameters were more accurate.

The three methodologies, i.e. the common protocol used in published works, three-steps-mean protocol and the suggested alternative statistical methodology, can also be compared more closely by comparing the results of a specific parameter across all three methods. For instance, Table 6.8 shows the results of peak pressure across the three protocols.

From that table, the alternative statistical methodology again proved to be more accurate than the others.

Table 6.8: Results of contact area from three protocols of obese participants

| Masks | mean of 3 steps | | published | | alternative | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | M | SE |
| Whole foot | 151.03 | 3.16 | 116.60 | 16.00 | 149.74 | 3.10 |
| Heel | 43.00 | 0.37 | 30.30 | 4.70 | 42.92 | 0.37 |
| Midfoot | 25.54 | 1.37 | 30.70 | 8.00 | 25.69 | 1.35 |
| Forefoot | 55.90 | 0.30 | 49.10 | 5.60 | 55.88 | 0.29 |
| Hallux | 10.75 | 0.24 | 10.20 | 1.60 | 10.74 | 0.23 |
| Toes | 5.58 | 1.38 | 10.20 | 2.50 | 6.66 | 1.21 |

### 6.2.2 Multiple publications for combining procedures by variance

To apply the suggested alternative statistical methodology on data from self-captured trials and multiple publications, the results of Butterworth et al. (2015), Walsh et al. (2017) and Walsh et al. (2018) were used. The results are presented in Tables 6.1, 6.9 and 6.10.

The proposed protocol, i.e. three-steps-mean over a large number of trials with a small number of participants, gave data of higher quality than those used in the published works. This can be seen by comparing the results of the proposed protocol, i.e. Table 6.2, and those of the published works, i.e. Tables 6.1, 6.9 and 6.10. All common parameters show that the standard deviations of the proposed protocol were smaller than those of Butterworth et al. (2015), Walsh et al. (2017) and Walsh et al. (2018).

Table 6.9: Results from Walsh et al. (2017)

| Masks | MF (kg) | | CA (cm) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 71.00 | 22.10 | 112.70 | 16.70 |
| **Heel** | 41.90 | 12.00 | 32.60 | 4.70 |
| **Midfoot** | 13.40 | 8.90 | 23.20 | 8.00 |
| **Forefoot** | 51.60 | 16.10 | 49.20 | 6.80 |
| **Hallux** | 8.20 | 2.70 | 10.60 | 1.60 |
| **Toes** | 4.50 | 1.90 | 11.00 | 2.40 |

MF: maximum force; CA: contact area; SD: standard deviation

Table 6.10: Results from Walsh et al. (2018)

| Masks | MF (kg) | | CA (cm) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| **Whole foot** | 155.70 | 17.50 | 185.20 | 23.20 |
| **Heel** | 85.80 | 10.80 | 55.10 | 5.00 |
| **Midfoot** | 41.60 | 8.90 | 46.90 | 6.10 |
| **Forefoot** | 99.80 | 14.40 | 63.50 | 8.60 |
| **Hallux** | 36.10 | 13.10 | 35.90 | 13.30 |
| **Toes** | 30.80 | 9.10 | 31.70 | 6.90 |

MF: maximum force; CA: contact area; SD: standard deviation

Assigning weights by variance for data form the self-captured trials and published works was achieved using Equation 3.1. The weighting values are displayed in Tables 6.5, 6.6, 6.11 and 6.12.

Table 6.11: Weighting values for Walsh 2017 data by variance

| Masks | MF (kg) | | | | | CA (cm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 71.00 | 22.10 | 488.41 | 0.00 | 0.15 | 112.70 | 16.70 | 278.89 | 0.00 | 0.40 |
| **Heel** | 41.90 | 12.00 | 144.00 | 0.01 | 0.29 | 32.60 | 4.70 | 22.09 | 0.05 | 1.48 |
| **Midfoot** | 13.40 | 8.90 | 79.21 | 0.01 | 0.17 | 23.20 | 8.00 | 64.00 | 0.02 | 0.36 |
| **Forefoot** | 51.60 | 16.10 | 259.21 | 0.004 | 0.20 | 49.20 | 6.80 | 46.24 | 0.02 | 1.06 |
| **Hallux** | 8.20 | 2.70 | 7.29 | 0.14 | 1.12 | 10.60 | 1.60 | 2.56 | 0.39 | 4.14 |
| **Toes** | 4.50 | 1.90 | 3.61 | 0.28 | 1.25 | 11.00 | 2.40 | 5.76 | 0.17 | 1.91 |

MF: maximum force; CA: contact area; SD: standard deviation; var: variance; wi: weight

Table 6.12: Weighting values for Walsh 2018 data by variance

| Masks | MF (kg) | | | | | CA (cm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **var** | **wi** | **mean*wi** | **Mean** | **SD** | **var** | **wi** | **mean*wi** |
| **Whole foot** | 155.70 | 17.50 | 306.25 | 0.00 | 0.51 | 185.20 | 23.20 | 538.24 | 0.00 | 0.34 |
| **Heel** | 85.80 | 10.80 | 116.64 | 0.01 | 0.74 | 55.10 | 5.00 | 25.00 | 0.04 | 2.20 |
| **Midfoot** | 41.60 | 8.90 | 79.21 | 0.01 | 0.53 | 46.90 | 6.10 | 37.21 | 0.03 | 1.26 |
| **Forefoot** | 99.80 | 14.40 | 207.36 | 0.005 | 0.48 | 63.50 | 8.60 | 73.96 | 0.01 | 0.86 |
| **Hallux** | 36.10 | 13.10 | 171.61 | 0.01 | 0.21 | 35.90 | 13.30 | 176.89 | 0.01 | 0.20 |
| **Toes** | 30.80 | 9.10 | 82.81 | 0.01 | 0.37 | 31.70 | 6.90 | 47.61 | 0.02 | 0.67 |

MF: maximum force; CA: contact area; SD: standard deviation; var: variance; wi: weight

Moreover, Equations 3.6 and 3.7 were used to calculate the final results of the alternative statistical methodology for obese participants combined with multiple publications and these are presented in Table 6.13.

Table 6.13: Results of alternative statistical methodology by variance for obese participants (combined with multiple publication)

| Masks | MF (kg) | | CA (cm) | |
|---|---|---|---|---|
| | **M** | **SE** | **M** | **SE** |
| **Whole foot** | 130.31 | 4.39 | 149.12 | 3.03 |
| **Heel** | 82.72 | 3.61 | 42.92 | 0.37 |
| **Midfoot** | 23.79 | 2.21 | 26.59 | 1.30 |
| **Forefoot** | 103.45 | 4.65 | 55.88 | 0.29 |
| **Hallux** | 15.88 | 1.38 | 10.75 | 0.23 |
| **Toes** | 3.82 | 0.84 | 8.11 | 1.06 |

MF: maximum force; CA: contact area; M: weighted mean; SE: standard error

## 6.3 Results

This section discusses the results of the proposed innovative statistical methodology of the obese participants for both cases, namely combining with single publication and combining with multiple publications.

### 6.3.1 Combining with one publication

The results of combining with one publication, i.e. Butterworth et al. (2015), for the obese participants are presented in Table 6.7. From this table and with respect to:

(A) Maximum force (MF) and contact area (CA)

(1.) The whole foot had the largest values of maximum force and contact area at 131.14 (4.64) kg and 149.74 (3.10) $cm^2$, respectively

(2.) The second highest values of these two parameters were under the region of the forefoot, 109.26 (5.17) kg for maximum force and 55.88 (0.29) $cm^2$ for contact area

(3.) Maximum force was followed by the heel at (86.93 (4.05) kg), and the midfoot at (23.27 (2.35) kg) in descending order

(4.) The same regions had the third and forth biggest values of the contact area. That is 43.92 (0.37) $cm^2$ and 25.69 (1.35) $cm^2$ for the heel and midfoot, respectively.

(5.) The toes regions had the lowest values for both maximum and contact area. The areas of hallux and toes had maximum force at 18.33 (1.62) kg and 3.36 (0.94)kg, respectively.

(6.) The contact area of the hallux region was 10.74 (0.23) $cm^2$, and the toes area was 6.66 (1.21) $cm^2$.

These results are presented in Figures 6.2 and 6.3.

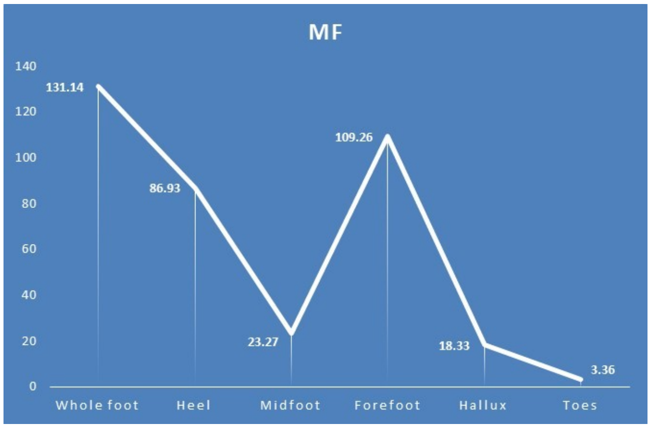


Figure 6.2: Results of combining with one publication (MF)

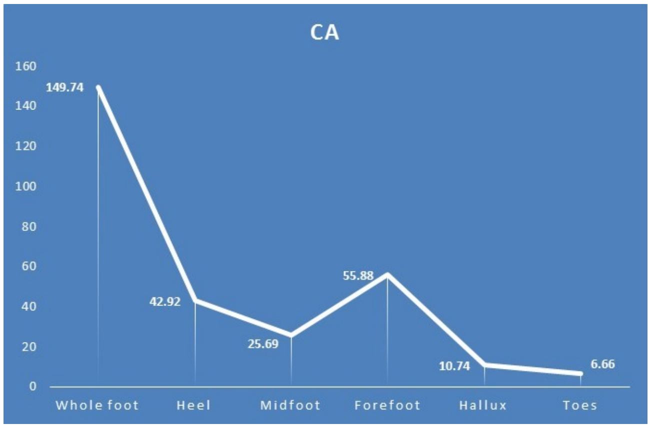


Figure 6.3: Results of combining with one publication (CA)

(B) Peak pressure (PP)

(1.) The heel area had the highest value of peak pressure at 3.71 (0.21) kg/cm$^2$, followed by the forefoot area at 3.63 (0.21) kg/cm$^2$.

(2.) The smallest values of peak pressure were under the midfoot and the toes areas at 1.95 (0.18) kg/cm$^2$ and 0.92 (0.14) kg/cm$^2$, respectively.

Figure 6.4 shows the results of the peak pressure parameter.

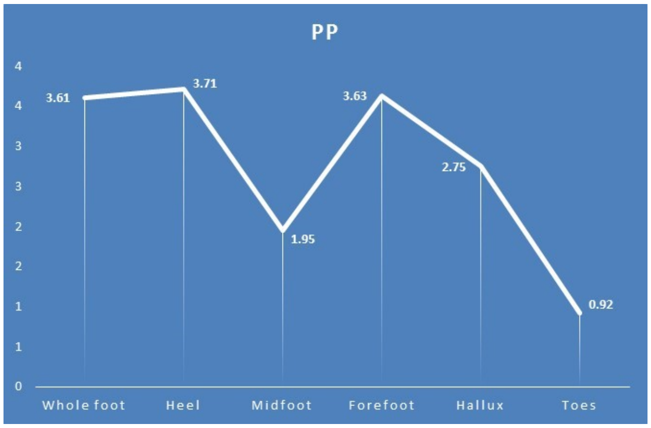


Figure 6.4: Results of combining with one publication (PP)

### 6.3.2 Combining with multiple publications

The results of applying the proposed statistical methodology to combine self-captured data with those of multiple publications, i.e. Table 6.13, show:

(A) For the maximum force (MF) parameter as presented in Figure 6.5:

1. The highest value was under the area of the whole foot (131.14 (4.64) kg).
2. The second highest value was under the forefoot area (109.26 (5.17) kg).
3. This was followed by the area of heel and midfoot at 86.93 (4.05)kg and 23.27 (2.35) kg, respectively.
4. The toes area had the lowest values of maximum force (MF): hallux (18.33 (1.62) kg) and toes (3.36 (0.94) kg).

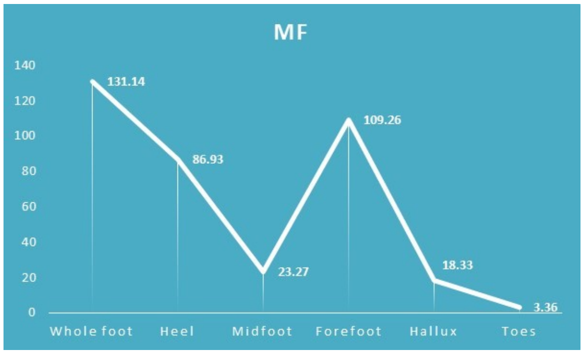


Figure 6.5: Results of combining with multiple publications (MF)

(B) For the contact area (CA) parameter and presented in Figure 6.6:

1. The whole foot area had the highest contact area (149.74 (3.10) $cm^2$).
2. The forefoot area had the second highest value for contact area (55.88 (0.29) $cm^2$)
3. The contact areas under the heel and midfoot regions were (42.92 (0.37) $cm^2$ and 25.69 (1.35) $cm^2$, respectively).

4. The smallest contact area was under the toes at (6.66 (1.21) $cm^2$); whereas, the hallux had (10.74 (0.23) $cm^2$).

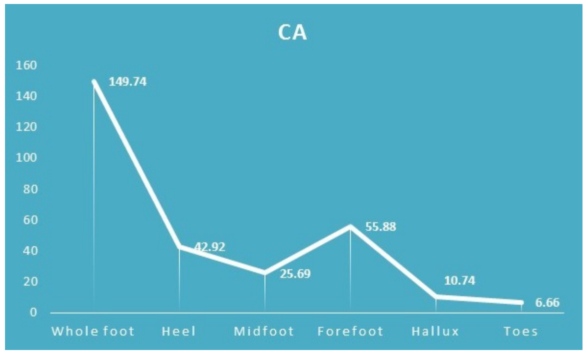


Figure 6.6: Results of combining with multiple publications (CA)

## 6.4 Discussion

Analysing parameters of pressure beneath the foot of the obese adults using the innovative statistical methodology rather than the most commonly used method in published works gave more accurate results. It performed better across all parameters studied in both cases, namely combining with one publication and multiple publications. The data of all parameters studied with the proposed protocol, i.e. three-steps-mean protocol, were normally distributed. They also had good to excellent reliability.

As a result, the first aim of this study, proving the effectiveness of the alternative proposed statistical methodology in analysing pressure parameters of obese adults, was achieved.

The other aim of this study was also achieved by establishing a range of values of maximum force (MF), contact area (CA) and peak pressure (PP). The findings with respect to these parameters were consistent with those of Butterworth et al. (2015), Walsh et al. (2017) and Walsh et al. (2018).

For maximum force (MF) parameter, the findings were in agreement with those of the published works in both cases: combining with one publication and combining with multiple publications. Those studies, and ours, found that the whole foot area had the largest maximum force, followed by the areas of forefoot, heel, midfoot, respectively. Whereas, the maximum force parameter was lowest in ascending order in the area of toes and hallux.

For the contact area (CA) parameter and in both combination cases, there was agreement between our findings and those of the published works. They all found that the two highest contact areas were under the whole foot and forefoot (in descending order). Whereas, the area of hallux and toes had the two lowest contact areas.

In addition, the findings of the current study in the case of combining with one publication were in agreement with those of Butterworth et al. (2015) for the parameter of peak pressure (PP). Both studies found that last three lowest values of peak pressure were in the areas of hallux, midfoot and toes (in descending order).

## 6.5 Conclusion

The main goal of this chapter was to present the results from a study of human gait parameters of obese adult participants. This goal is associated with secondary goals, namely using the innovative statistical methodology to anlayse some characteristics of obese adults, highlighting the effectiveness of it compared with other methodologies used in the literature.

The developed method obtained better results. They were more accurate than those found in the mentioned published works in the case of combining self-captured data with data from one publication and multiple publications. The second secondary goal was to establish more accurate value ranges of the parameters examined in this study.

Thus, the outcomes of the current study add to the body of knowledge of human gait analysis: the proposed alternative methodology which is more reliable than the commonly used methodologies. Experts and researchers who are dealing with the gait problems of obese people can use this methodology to obtain better results in more efficient way.

# Chapter 7

# Conclusion

This chapter introduces the overall findings of this research. In addition, it suggests some areas for future possible research.

## 7.1 Conclusion

Due to the need for a more efficient approach to conducting human gait analysis, this research proposed an innovative statistical methodology. The main benefit of this methodology is that it requires a smaller number of study participants, which means the expenditure of fewer resources (effort, time and money). In addition, it provides more accurate results.

The new methodology works by combining more accurate self-captured data and published data. Hence, it requires new protocols to collect the more accurate self-captures data, and techniques to combine these with the published data and to calculate the final results. Therefore, two new protocols, one step and mean of three steps, were proposed to collect human gait from a small number of participants over a large number of trials. By using these protocols, highly accurate data were obtained. Furthermore, some statistical techniques were used to combine data from both sources by weighting them, and other statistical techniques were employed to compute the final results from the combined data.

For the first group of participants, healthy young adults, 70 parameters of the pressure beneath the foot were studied. They were contact area ($cm^2$), mean force (N), peak pressure (kPa), pressure-time integral (kPa s), force-time integral (N s), maximum force (N) and mean area ($cm^2$) from ten foot regions: heel, midfoot, first metatarsal (MTH1), second metatarsal (MTH2), third metatarsal (MTH3), fourth metatarsal (MTH4), fifth metatarsal (MTH5), hallux, second toe and third-fifth toes. The suggested protocol gave more accurate results in more than (91.4%) of the parameters studied compared to published results: 91.4% compared to Ramanathan et al. (2010), 97.5% compared to Putti et al. (2007), 97.5% compared to Putti et al. (2008) and 95.8% compared to Maetzler et al. (2010). In addition, analysing these parameters using the proposed innovative statistical methodology led to more accurate results for all parameters (100%) in all cases, i.e. combining with single publication (using var and CV) and combining with multiple publications (using var and CV).

The second study dealt with healthy older adults. In this study, data of 20 parameters were examined. They were maximum force (N), contact area ($cm^2$), peak pressure (kPa), pressure time integral (kPa s) and force time integral (N s) from the whole foot and three foot regions: rearfoot, midfoot and forefoot. In comparison with the results of McKay et al. (2017), the new protocol achieved better results in (95%) of the parameters studied. The proposed statistical methodology gave more accurate results for all parameters (100%) in both cases, i.e. combining with single and multiple publications.

The participants of the third group were obese adults. The parameters of maximum force (kg), contact area ($cm^2$) and peak pressure ($kg/cm^2$) from six foot regions, i.e. wholefoot, heel, midfoot, forefoot, hallux and toes. In 94.5% of parameters examined, the proposed protocol lead to more accurate results compared to those of Butterworth et al. (2015). Furthermore, the alternative statistical methodology achieved more accurate results when combining with single and multiple publications in all parameters (100%).

Additionally, reliability was good in all three studies. In the first study, calculating the Coefficient of Variation (CV) indicated that reliability was greater for 66 of 70 parameters compared to Ramanathan et al. (2010). In the second and third study, the ICC values indicated that the reliability was good to excellent.

To conclude, the innovative statistical methodology performed better than techniques most commonly used in the field of human gait analysis. Therefore, using such an approach will help those who work in gait related medical and sports areas. The particular research and practice gains are:

- Better human gait analysis as it helps to improve the sample size.
- More accurate results which help experts to establish closer values to the real values of gait parameters
- Better understanding of human gait characteristics due to the determination of more accurate values of gait parameters
- Better diagnoses and treatments for those who have medical conditions that impact their ability to walk normally.

To sum up, Table 7.1 presents an overview of all main points investigated in this thesis.

Table 7.1: Overview of all investigated main points

| Main Point | Details |
|---|---|
| Human gait data collection | Two protocols (one-step and three-steps-mean protocols) were proposed to collect highly accurate human gait data by recruiting a small number of participants over a big number of trials. |
| Combining data and finding final results | The innovative statistical methodology involves combining data from several sources using Equations 3.5, 3.3, 3.2, 3.4 or 3.1. After that Equations 3.6 and 3.7 are used to find the final results. |
| Groups of participants | Three groups of participants were studied: 1) healthy young adults, 2) healthy older adults and 3) obese adults. |
| Gait characteristics | Each study of this thesis investigated several gait characteristics. For the first groups, the characteristics were: contact area (CA) $cm^2$, mean force (MeF) N, peak pressure (PP) kPa, pressure-time integral (PTI) kPa s, force-time integral (FTI) N s, maximum force (MF) N and mean area (MeA) $cm^2$. For the second group, the characteristics were: maximum force (MF) N, contact area (CA) $cm^2$, peak pressure (PP) kPa, pressure time integral (PTI) kPa s and force time integral (FTI) N s. While the characteristics of the third group were: maximum force (MF) kg, contact area (CA) $cm^2$ and peak pressure (PP) $kg/cm^2$. |
| Foot regions | Various foot regions were used in each study. In the first study, the foot was divided into ten regions: heel, midfoot, first metatarsal (MTH1), second metatarsal (MTH2), third metatarsal (MTH3), fourth metatarsal (MTH4), fifth metatarsal (MTH5), hallux, second toe and third-fifth toes as shown in Figure 4.1. In the second study, In the second study, data were collected from: the whole foot, rearfoot, midfoot and forefoot. While, six foot regions were used in the last study: whole foot, heel, midfoot, forefoot, hallux and toes |

## 7.2 Future Works

There are possibilities of future research related to the concept explored in this thesis. First, the innovative statistical methodology can be use to analyse human gait characteristics of many other groups of people such as diabetics, orthoses users, those with neurological and systemic diseases. Secondly, many other human gait characteristics can be examined using the new approach. For instance gait speed, cadence, stride length, step length, stance time, EMG and many more. Thirdly, the new methodology can be used to investigate various circumstances of gait testing-such as barefoot versus shod gait, and ascending and descending stairs versus level walking. It might also be used in sporting research by establishing more accurate results to improve athletes' performance.

# References


Abdul Razak, A. H., Zayegh, A., Begg, R. K. & Wahab, Y. (2012), 'Foot plantar pressure measurement system: A review', *Sensors* **12**(7), 9884–9912.

Akhtaruzzaman, M., Shafie, A. A. & Khan, M. R. (2016), 'Gait analysis: Systems, technologies, and importance', *Journal of Mechanics in Medicine and Biology* **16**(07), 1630003.

Almarwani, M., Perera, S., VanSwearingen, J. M., Sparto, P. J. & Brach, J. S. (2016), 'The test–retest reliability and minimal detectable change of spatial and temporal gait variability during usual over-ground walking for younger and older adults', *Gait & posture* **44**, 94–99.

Anandacoomarasamy, A., Caterson, I., Sambrook, P., Fransen, M. & March, L. (2008), 'The impact of obesity on the musculoskeletal system', *International journal of obesity* **32**(2), 211.

Arts, M. & Bus, S. (2011), 'Twelve steps per foot are recommended for valid and reliable in-shoe plantar pressure data in neuropathic diabetic patients wearing custom made footwear', *Clinical biomechanics* **26**(8), 880–884.

Atkinson, G. & Nevill, A. M. (1998), 'Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine', *Sports medicine* **26**(4), 217–238.

Bae, K.-H., Shin, J.-H., Lee, J.-S., Yang, J.-O., Lee, B.-J. & Park, S.-B. (2016), 'Analyses of plantar foot pressure and static balance according to the type of insole in the elderly', *Korean Journal of Sport Biomechanics* **26**(1), 115–126.

Baker, R. (2006), 'Gait analysis methods in rehabilitation', *Journal of neuroengineering and rehabilitation* **3**(1), 4.

Begg, R. & Kamruzzaman, J. (2005), 'A machine learning approach for automated recognition of movement patterns using basic, kinetic and kinematic gait data', *Journal of biomechanics* **38**(3), 401–408.

Borenstein, M., Hedges, L. V., Higgins, J. P. & Rothstein, H. R. (2011), *Introduction to meta-analysis*, John Wiley & Sons.

Bosch, K., Nagel, A., Weigend, L. & Rosenbaum, D. (2009), 'From first to last steps in life–pressure patterns of three generations', *Clinical Biomechanics* **24**(8), 676–681.

Brach, J. S., Perera, S., Studenski, S. & Newman, A. B. (2008), 'The reliability and validity of measures of gait variability in community-dwelling older adults', *Archives of physical medicine and rehabilitation* **89**(12), 2293–2296.

Brehm, M.-A., Harlaar, J. & Schwartz, M. (2008), 'Effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy', *Journal of rehabilitation medicine* **40**(7), 529–534.

Brown, J. D. (2007), 'Sample size and statistical precision', *Statistics* **11**(2).

Bruton, A., Conway, J. H. & Holgate, S. T. (2000), 'Reliability: what is it, and how is it measured?', *Physiotherapy* **86**(2), 94–99.

Burnfield, J. M., Few, C. D., Mohamed, O. S. & Perry, J. (2004), 'The influence of walking speed and footwear on plantar pressures in older adults', *Clinical Biomechanics* **19**(1), 78–84.

Bus, S. A. & de Lange, A. (2005), 'A comparison of the 1-step, 2-step, and 3-step protocols for obtaining barefoot plantar pressure data in the diabetic neuropathic foot', *Clinical biomechanics* **20**(9), 892–899.

Butterworth, P. A., Landorf, K. B., Smith, S. & Menz, H. B. (2012), 'The association between body mass index and musculoskeletal foot disorders: a systematic review', *Obesity reviews* **13**(7), 630–642.

Butterworth, P. A., Urquhart, D. M., Landorf, K. B., Wluka, A. E., Cicuttini, F. M. & Menz, H. B. (2015), 'Foot posture, range of motion and plantar pressure characteristics in obese and non-obese individuals', *Gait & posture* **41**(2), 465–469.

Catalfamo, P., Moser, D., Ghoussayni, S. & Ewins, D. (2008), 'Detection of gait events using an f-scan in-shoe pressure measurement system', *Gait & posture* **28**(3), 420–426.

Cheung, J. T.-M. & Zhang, M. (2006), Finite element modeling of the human foot and footwear, *in* 'ABAQUS users conference', pp. 145–58.

Chevalier, T. L., Hodgins, H. & Chockalingam, N. (2010), 'Plantar pressure measurements using an in-shoe system and a pressure platform: A comparison', *Gait & posture* **31**(3), 397–399.

Chuckpaiwong, B., Nunley, J. A., Mall, N. A. & Queen, R. M. (2008), 'The effect of foot type on in-shoe plantar pressure during walking and running', *Gait & posture* **28**(3), 405–411.

Cochran, W. G. (1937), 'Problems arising in the analysis of a series of similar experiments', *Supplement to the Journal of the Royal Statistical Society* **4**(1), 102–118.

Cordero, A. F., Koopman, H. & Van Der Helm, F. (2004), 'Use of pressure insoles to calculate the complete ground reaction forces', *Journal of biomechanics* **37**(9), 1427–1432.

Csapo, R., Maganaris, C., Seynnes, O. & Narici, M. (2010), 'On muscle, tendon and high heels', *Journal of Experimental Biology* **213**(15), 2582–2588.

Cunado, D., Nixon, M. S. & Carter, J. N. (2003), 'Automatic extraction and description of human gait models for recognition purposes', *Computer Vision and Image Understanding* **90**(1), 1–41.

Davis, R. B. (1997), 'Reflections on clinical gait analysis', *Journal of Electromyography and Kinesiology* **7**(4), 251–257.

Debbi, E. M., Wolf, A., Goryachev, Y., Yizhar, Z., Luger, E., Debi, R. & Haim, A. (2012), 'In-shoe center of pressure: Indirect force plate vs. direct insole measurement', *The Foot* **22**(4), 269–275.

Di Stasi, S. L., Logerstedt, D., Gardinier, E. S. & Snyder-Mackler, L. (2013), 'Gait patterns differ between acl-reconstructed athletes who pass return-to-sport criteria and those who fail', *The American journal of sports medicine* **41**(6), 1310–1318.

Fathima, S. S. S. & Banu, R. W. (2012), Human gait recognition based on motion analysis including ankle to foot angle measurement, *in* 'Computing, Electronics and Electrical Technologies (ICCEET), 2012 International Conference on', IEEE, pp. 1133–1136.

Giacomozzi, C. & Uccioli, L. (2013), 'Learning from experience: A simple effective protocol to test footwear prescriptions for the diabetic foot by using the pedar system', *Journal of Biomedical Science and Engineering* **6**(05), 45.

Goffredo, M., Bouchrika, I., Carter, J. N. & Nixon, M. S. (2010), 'Performance analysis for automated gait extraction and recognition in multi-camera surveillance', *Multimedia Tools and Applications* **50**(1), 75–94.

Gregor, M. F. & Hotamisligil, G. S. (2011), 'Inflammatory mechanisms in obesity', *Annual review of immunology* **29**, 415–445.

Gurney, J. K., Kersting, U. G. & Rosenbaum, D. (2008), 'Between-day reliability of repeated plantar pressure distribution measurements in a normal population', *Gait & posture* **27**(4), 706–709.

Gwet, K. L. (2014), *Handbook of inter-rater reliability: The definitive guide to measuring the extent of agreement among raters*, Advanced Analytics, LLC.

Hafer, J. F., Lenhoff, M. W., Song, J., Jordan, J. M., Hannan, M. T. & Hillstrom, H. J. (2013), 'Reliability of plantar pressure platforms', *Gait & posture* **38**(3), 544–548.

Harris, G. F. & Wertsch, J. J. (1994), 'Procedures for gait analysis', *Archives of Physical Medicine and Rehabilitation* **75**(2), 216–225.

Healy, A., Burgess-Walker, P., Naemi, R. & Chockalingam, N. (2012), 'Repeatability of walkinsense® in shoe pressure measurement system: A preliminary study', *The Foot* **22**(1), 35–39.

Henriksen, M., Lund, H., Moe-Nilssen, R., Bliddal, H. & Danneskiod-Samsøe, B. (2004), 'Test–retest reliability of trunk accelerometric gait analysis', *Gait & posture* **19**(3), 288–297.

Hessert, M. J., Vyas, M., Leach, J., Hu, K., Lipsitz, L. A. & Novak, V. (2005), 'Foot pressure distribution during walking in young and old adults', *BMC geriatrics* **5**(1), 8.

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

Hopkins, W. G. (2000), 'Measures of reliability in sports medicine and science', *Sports medicine* **30**(1), 1–15.

Izquierdo-Renau, M., Pérez-Soriano, P., Ribas-García, V. & Queralt, A. (2017), 'Intra and intersession repeatability and reliability of the s-plate® pressure platform', *Gait & posture* **52**, 224–226.

Kale, A., Cuntoor, N., Yegnanarayana, B., Rajagopalan, A. & Chellappa, R. (2003), Gait analysis for human identification, *in* 'International Conference on Audio-and Video-Based Biometric Person Authentication', Springer, pp. 706–714.

Keenan, G. S., Franz, J. R., Dicharry, J., Della Croce, U. & Kerrigan, D. C. (2011), 'Lower limb joint kinetics in walking: the role of industry recommended footwear', *Gait & posture* **33**(3), 350–355.

Kerrigan, D. C., Lelas, J. L. & Karvosky, M. E. (2001), 'Women's shoes and knee osteoarthritis', *The Lancet* **357**(9262), 1097–1098.

Kerrigan, D. C., Todd, M. K. & Riley, P. O. (1998), 'Knee osteoarthritis and high-heeled shoes', *The Lancet* **351**(9113), 1399–1401.

Khodaei, B., Saeedi, H., Farzadi, M., Norouzi, E. et al. (2017), 'Comparison of plantar pressure distribution in cad–cam and prefabricated foot orthoses in patients with flexible flatfeet', *The Foot* **33**, 76–80.

Kimmeskamp, S. & Hennig, E. M. (2001), 'Heel to toe motion characteristics in parkinson patients during free walking', *Clinical biomechanics* **16**(9), 806–812.

Kirtley, C. (2006), *Clinical gait analysis: theory and practice*, Elsevier Health Sciences.

König, N., Singh, N. B., Von Beckerath, J., Janke, L. & Taylor, W. R. (2014), 'Is gait variability reliable? an assessment of spatio-temporal parameters of gait variability during continuous overground walking', *Gait & posture* **39**(1), 615–617.

Koo, T. K. & Li, M. Y. (2016), 'A guideline of selecting and reporting intraclass correlation coefficients for reliability research', *Journal of chiropractic medicine* **15**(2), 155–163.

Lee, L. & Grimson, W. E. L. (2002), Gait analysis for recognition and classification, *in* 'Automatic Face and Gesture Recognition, 2002. Proceedings. Fifth IEEE International Conference on', IEEE, pp. 155–162.

Levine, D., Richards, J. & Whittle, M. W. (2012), *Whittle's Gait Analysis-E-Book*, Elsevier Health Sciences.

Lexell, J. E. & Downham, D. Y. (2005), 'How to assess the reliability of measurements in rehabilitation', *American journal of physical medicine & rehabilitation* **84**(9), 719–723.

Liaw, L.-J., Hsieh, C.-L., Lo, S.-K., Chen, H.-M., Lee, S. & Lin, J.-H. (2008), 'The relative and absolute reliability of two balance performance measures in chronic stroke patients', *Disability and rehabilitation* **30**(9), 656–661.

Maetzler, M., Bochdansky, T. & Abboud, R. (2010), 'Normal pressure values and repeatability of the emed® st2 system', *Gait & Posture* **32**(3), 391–394.

Martínez-Nova, A., Cuevas-García, J. C., Pascual-Huerta, J. & Sánchez-Rodríguez, R. (2007), 'Biofoot® in-shoe system: Normal values and assessment of the reliability and repeatability', *The Foot* **17**(4), 190–196.

McKay, M. J., Baldwin, J. N., Ferreira, P., Simic, M., Vanicek, N., Wojciechowski, E., Mudge, A. & Burns, J. (2017), 'Spatiotemporal and plantar pressure patterns of 1000 healthy individuals aged 3–101 years', *Gait & posture* **58**, 78–87.

Menz, H. B. (2005), 'Analysis of paired data in physical therapy research: time to stop double-dipping?'.

Menz, H. B., Latt, M. D., Tiedemann, A., San Kwan, M. M. & Lord, S. R. (2004), 'Reliability of the gaitrite® walkway system for the quantification of temporo-spatial parameters of gait in young and older people', *Gait & posture* **20**(1), 20–25.

Menz, H. B. & Morris, M. E. (2006), 'Clinical determinants of plantar forces and pressures during walking in older people', *Gait & posture* **24**(2), 229–236.

Mikhail, E. M. & Gracie, G. (1981), *Analysis and adjustment of survey measurements*, Van Nostrand Reinhold New York.

Miner-Williams, W. (2017), 'The accuracy and reliability of plantar pressure measurements for the early diagnosis of foot deformities in patients suffering from rheumatoid arthritis', *Diversity and Equality in Health and Care* **14**(4), 193–202.

Motawea, M., El-Nahas, M. & Armstrong, D. G. (2019), 'Pressure distribution under the contralateral limb in charcot arthropathy with different gait speeds', *The Foot* .

Muro-De-La-Herran, A., Garcia-Zapirain, B. & Mendez-Zorrilla, A. (2014), 'Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications', *Sensors* **14**(2), 3362–3394.

Organization, W. H. (2000), *Obesity: preventing and managing the global epidemic*, number 894, World Health Organization.

Orlin, M. N. & McPoil, T. G. (2000), 'Plantar pressure assessment', *Physical therapy* **80**(4), 399–409.

Perry, J., Burnfield, J. M. & Cabico, L. M. (2010), *Gait analysis: normal and pathological function*, second edn, SLACK, Thorofare, NJ.

Putti, A., Arnold, G. & Abboud, R. (2010), 'Foot pressure differences in men and women', *Foot and ankle surgery* **16**(1), 21–24.

Putti, A., Arnold, G., Cochrane, L. & Abboud, R. (2007), 'The pedar® in-shoe system: Repeatability and normal pressure values', *Gait & posture* **25**(3), 401–405.

Putti, A., Arnold, G., Cochrane, L. & Abboud, R. (2008), 'Normal pressure values and repeatability of the emed® st4 system', *Gait & posture* **27**(3), 501–505.

Rai, D. & Aggarwal, L. (2006), 'The study of plantar pressure distribution in normal and pathological foot', *Pol J Med Phys Eng* **12**(1), 25–34.

Ramanathan, A., Kiran, P., Arnold, G., Wang, W. & Abboud, R. (2010), 'Repeatability of the pedar-x® in-shoe pressure measuring system', *Foot and Ankle Surgery* **16**(2), 70–73.

Rankin, G. & Stokes, M. (1998), 'Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses', *Clinical rehabilitation* **12**(3), 187–199.

Rao, S., Baumhauer, J. & Nawoczenski, D. (2011), 'Is barefoot regional plantar loading related to self-reported foot pain in patients with midfoot osteoarthritis', *Osteoarthritis and cartilage* **19**(8), 1019–1025.

Rao, S. & Carter, S. (2012), 'Regional plantar pressure during walking, stair ascent and descent', *Gait & posture* **36**(2), 265–270.

Reints, R., Hijmans, J. M., Burgerhof, J. G., Postema, K. & Verkerke, G. J. (2017), 'Effects of flexible and rigid rocker profiles on in-shoe pressure', *Gait & posture* **58**, 287–293.

Romkes, J. & Brunner, R. (2002), 'Comparison of a dynamic and a hinged ankle–foot orthosis by gait analysis in patients with hemiplegic cerebral palsy', *Gait & posture* **15**(1), 18–24.

Shakoor, N. & Block, J. A. (2006), 'Walking barefoot decreases loading on the lower extremity joints in knee osteoarthritis', *Arthritis & Rheumatism* **54**(9), 2923–2927.

Shrout, P. E. & Fleiss, J. L. (1979), 'Intraclass correlations: uses in assessing rater reliability.', *Psychological bulletin* **86**(2), 420.

Stöckel, T., Jacksteit, R., Behrens, M., Skripitz, R., Bader, R. & Mau-Moeller, A. (2015), 'The mental representation of the human gait in young and older adults', *Frontiers in psychology* **6**, 943.

Sutton, A. J., Abrams, K. R., Jones, D. R., Jones, D. R., Sheldon, T. A. & Song, F. (2000), 'Methods for meta-analysis in medical research'.

Tanamas, S. K., Wluka, A. E., Berry, P., Menz, H. B., Strauss, B. J., Davies-Tuck, M., Proietto, J., Dixon, J. B., Jones, G. & Cicuttini, F. M. (2012), 'Relationship between obesity and foot pain and its association with fat mass, fat distribution, and muscle mass', *Arthritis care & research* **64**(2), 262–268.

Tao, W., Liu, T., Zheng, R. & Feng, H. (2012), 'Gait analysis using wearable sensors', *Sensors* **12**(2), 2255–2283.

Tsushima, H., Morris, M. E. & McGinley, J. (2003), 'Test-retest reliability and inter-tester reliability of kinematic data from a three-dimensional gait analysis system', *Journal of the Japanese Physical Therapy Association* **6**(1), 9–17.

Vaz, S., Falkmer, T., Passmore, A. E., Parsons, R. & Andreou, P. (2013), 'The case for using the repeatability coefficient when calculating test–retest reliability', *PLoS One* **8**(9), e73990.

Wahab, Y. & Bakar, N. A. (2011), Gait analysis measurement for sport application based on ultrasonic system, *in* 'Consumer Electronics (ISCE), 2011 IEEE 15th International Symposium on', IEEE, pp. 20–24.

Walsh, T. P., Butterworth, P. A., Urquhart, D. M., Cicuttini, F. M., Landorf, K. B., Wluka, A. E., Shanahan, E. M. & Menz, H. B. (2017), 'Increase in body weight over a two-year period is associated with an increase in midfoot pressure and foot pain', *Journal of foot and ankle research* **10**(1), 31.

Walsh, T. P., Gill, T. K., Evans, A. M., Yaxley, A., Chisholm, J. A., Kow, L., Arnold, J. B. & Shanahan, E. M. (2018), 'Changes in foot pain, structure and function following bariatric surgery', *Journal of foot and ankle research* **11**(1), 35.

Watanabe, K. & Hokari, M. (2006), 'Kinematical analysis and measurement of sports form', *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* **36**(3), 549–557.

Wearing, S. C., Urry, S., Smeathers, J. E. & Battistutta, D. (1999), 'A comparison of gait initiation and termination methods for obtaining plantar foot pressures', *Gait & posture* **10**(3), 255–263.

Weir, J. P. (2005), 'Quantifying test-retest reliability using the intraclass correlation coefficient and the sem', *The Journal of Strength & Conditioning Research* **19**(1), 231–240.

Westphal, E., Carl, H.-D., Krinner, S., Grim, C., Swoboda, B. & Hotfiel, T. (2016), 'Plantar force deviations in dynamic pedobarography–the role of insole and platform based systems as influencing factors', *Sports Orthopaedics and Traumatology* **32**(4), 380–386.

Whittle, M. W. (1996), 'Clinical gait analysis: A review', *Human Movement Science* **15**(3), 369–387.

Winter, D. A. (2009), *Biomechanics and motor control of human movement*, John Wiley & Sons.

Yoo, J.-H., Hwang, D. & Nixon, M. S. (2005), Gender classification in human gait using support vector machine, *in* 'International Conference on Advanced Concepts for Intelligent Vision Systems', Springer, pp. 138–145.

Yousefi, J. & Hamilton-Wright, A. (2014), 'Characterizing emg data using machine-learning tools', *Computers in biology and medicine* **51**, 1–13.

Zammit, G. V., Menz, H. B. & Munteanu, S. E. (2010), 'Reliability of the tekscan matscan® system for the measurement of plantar forces and pressures during barefoot level walking in healthy adults', *Journal of foot and ankle research* **3**(1), 11.

Zammit, G. V., Menz, H. B., Munteanu, S. E. & Landorf, K. B. (2008), 'Plantar pressure distribution in older people with osteoarthritis of the first metatarsophalangeal joint (hallux limitus/rigidus)', *Journal of orthopaedic research* **26**(12), 1665–1669.

Zhang, R., Vogler, C. & Metaxas, D. (2004), Human gait recognition, *in* 'Computer Vision and Pattern Recognition Workshop, 2004. CVPRW'04. Conference on', IEEE, pp. 18–18.

# Appendix A

# Ethics Clearance Forms

## A.1 Participant Information Sheet

**To**: Participants

**Full Project Title**: An Alternative Statistical Methodology to Improve Human Gait Analysis.

**Principal Supervisor**: Dr. Albert K. Chong

**Principal Researcher**: Kadhem Al-Daffaie

**Application ID**: H18REA162

I am a PhD student at the University of Southern Queensland and my research is related to the area of statistical methodologies used to analyse human gait. Through my PhD, I aim to introduce an alternative methodology to conduct human gait studies. I identified a gap in the research in this area and I believe that through my research I will be able to provide more accurate results of plantar pressure assessments by using the suggested alternative methodology. It will help experts, especially in the medical sector, to provide better diagnosis and then treatments to those who have issues with their ability to walk normally. I would therefore like to invite you to take part in this research project. You are invited to participate in this research project because I believe that this research will be beneficial for the medical community in a way that can help them to improve the current human plantar assessment techniques.

Please read the following statements carefully. They have been written to explain all the procedures involved so you can make a fully informed decision to participate or not. Feel free to ask questions about any information in the document. You may also wish to discuss the project with a relative, friend or doctor. Once you understand what the project is about and agree to take part in it, please sign the Consent Form. By signing the Consent Form, you indicate that you have understood the information and that you give your consent to participate in the research project.

1. **Purpose of Research**

   The purpose of this project is to introduce an alternative statistical methodology in the field of human gait analysis. This methodology will help experts to reduce time, effort and money to conduct such analysis. This research is a part of a PhD degree. The current techniques used to collect and analyse data in the field of human gait require a large number of participants to do trials. However, this research is trying to provide an alternative methodology that can enable researchers to recruit a smaller number of participants when conducting human gait analysis, which results in reducing the cost, time and effort.

2. **Procedures**

   Participation in this project will involve:

   (a) Visiting the venue

   Participants need to come to the Photogrammetry lab which is located on the ground floor in S block at USQ/Toowoomba.

(b) Preparation for pressure capturing

Participants will be given appropriate sized shoes with insole sensors inside them, and then be connected to a computer.

(c) Pressure recording

Participants will be asked to walk along the lab (about 10 metres) to record the pressure beneath the feet.

(d) After recording

One of the investigators will remove the shoes with the sensors.

The whole experiment will take approximately 30-40 minutes. Some basic characteristics will be recorded about each participant, namely: age, gender, height and weight. All the researchers involved in this study will be available during the study to provide assistance and answer any participant questions. The participants will be a part of a novel study and if they wish to have any follows ups on the final results of the study, they can contact the researchers. There will be almost no any kind of risks during the trials as the participants will be walking at their normal speed and the researchers will make sure that the walkway is clear. In addition, this research does not involve any kind of health or foot assessment.

3. **Confidentiality**

The raw pressure records for each participant will be immediately downloaded and then stored in a password protected research computer at USQ, which no one has access to other than the researchers involved in the study. The data will be stored until the PhD studies have been completed. Any information obtained in connection with this project that can identify participants will remain confidential. Personal information such as names or images that can lead to the identification of the participant will not be included at any stage of this study. Information regarding gender and weight of participants may be published but information regarding participant identity will be removed. The data might be used in future for similar purposes such as introducing new other statistical methodologies in the field of human gait analysis.

4. **Voluntary Participation**

   Participation is entirely voluntary. If you do not wish to take part you are not obliged to. If you decide to take part and change your mind later, you are free to withdraw from the project at any stage. Any information already obtained from you will be destroyed. Before you make your decision, a member of the research team will be available to answer any questions you have about the research project. You can ask about any information you want. Sign the Consent Form only after you have had a chance to ask questions and have received satisfactory answers.

5. **Queries or Concerns**

   Should you have any queries regarding the progress or conduct of this research, you can contact the principal researcher:

   **Dr. Albert K. Chong**

   **Faculty of Engineering and Surveying**

   **Room Z412**

   **University of Southern Queensland**

   **Tel (+61) 7 4631 2546**

   **Mobile: 0420534762**

   If you have any concerns or complaints about the ethical conduct of the project you may contact the University of Southern Queensland Manager of Research Integrity and Ethics on **+61 7 4631 2214** or email **researchintegrity@usq.edu.au**.

## A.2 Consent Form

**To**: Participants

**Full Project Title**: An Alternative Statistical Methodology to Improve Human Gait Analysis.

**Principal Supervisor**: Dr. Albert K. Chong

**Principal Researcher**: Kadhem Al-Daffaie

**Application ID**: H18REA162

- 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 scan recorded of my plantar surface 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.

Name of participant ..........................................................

Signature ..................................... Date ....................

If you have any concerns or complaints about the ethical conduct of the project you may contact the University of Southern Queensland Manager of Research Integrity and Ethics on **+61 7 4631 2214** or email **researchintegrity@usq.edu.au**.

# Appendix B

# Results of Distribution tests and Outlier Detection: Healthy Young Adults

## B.1 Shapiro-Wilks test

This section includes the results of Shapiro-Wilks tests of 70 parameters, i.e. CA, MeF, PP, PTI, FTI, MF and MeA from the regions of the heel, midfoot, MTH1, MTH2, MTH3, MTH4, MTH5, hallux, 2nd toe and 3-5th toes, studied of the healthy young adults group.

Table B.1: Shapiro-Wilk test for CA of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.993 | 0.349 | 0.467 | 0.727 | 0.095 | 0.543 | 0.946 | 0.910 | 0.350 | 0.302 |

Table B.2: Shapiro-Wilk test for MeF of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.507 | 0.167 | 0.719 | 0.761 | 0.694 | 0.285 | 0.723 | 0.868 | 0.094 | 0.990 |

Table B.3: Shapiro-Wilk test for PP of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.043 | 0.766 | 0.198 | 0.595 | 0.818 | 0.562 | 0.550 | 0.701 | 0.289 | 0.865 |

Table B.4: Shapiro-Wilk test for PTI of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.375 | 0.934 | 0.225 | 0.418 | 0.578 | 0.384 | 0.493 | 0.571 | 0.610 | 0.591 |

Table B.5: Shapiro-Wilk test for FTI of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.549 | 0.379 | 0.685 | 0.532 | 0.498 | 0.240 | 0.367 | 0.996 | 0.237 | 0.948 |

Table B.6: Shapiro-Wilk test for MF of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.978 | 0.516 | 0.298 | 0.721 | 0.100 | 0.104 | 0.295 | 0.917 | 0.176 | 0.978 |

Table B.7: Shapiro-Wilk test for MeA of healthy young participants

| masks | **Heel** | **Midfoot** | **MTH1** | **MTH2** | **MTH3** | **MTH4** | **MTH5** | **Hallux** | **2nd toe** | **3-5th toes** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sig.** | 0.670 | 0.423 | 0.009 | 0.140 | 0.492 | 0.344 | 0.235 | 0.608 | 0.331 | 0.294 |

## B.2 Box-plots

This section includes the results of outlier detection of 70 parameters, i.e. CA, MeF, PP, PTI, FTI, MF and MeA from the regions of the heel, midfoot, MTH1, MTH2, MTH3, MTH4, MTH5, hallux, 2nd toe and 3-5th toes, studied of the healthy young adults group.

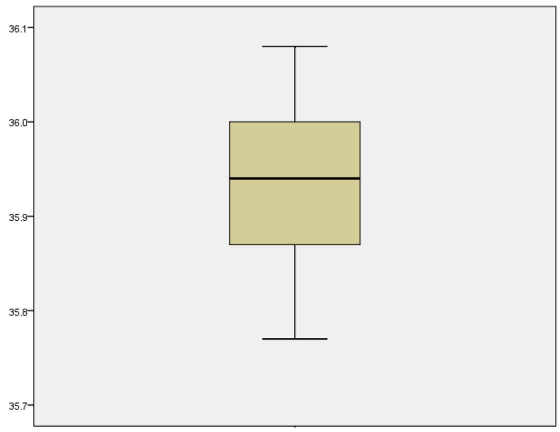


Figure B.1: CA at heel region for healthy young participants

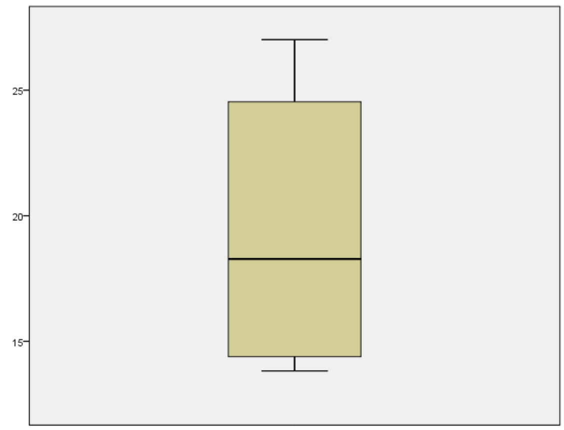


Figure B.2: CA at midfoot region for healthy young participants

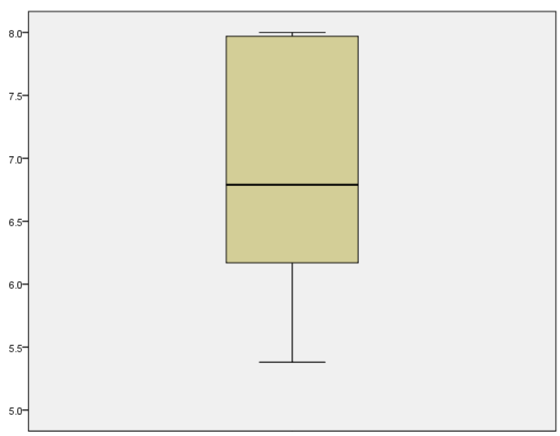


Figure B.3: CA at MTH1 region for healthy young participants

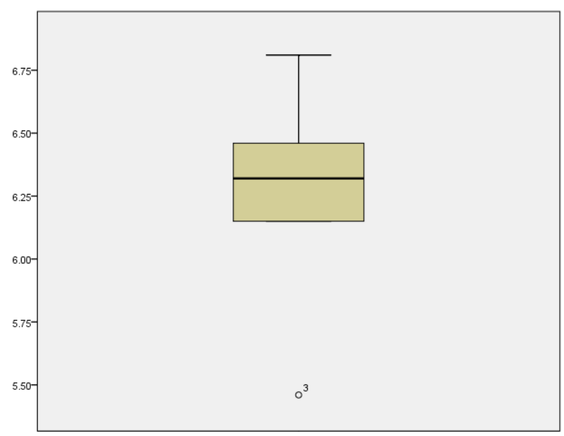


Figure B.4: CA at MTH2 region for healthy young participants

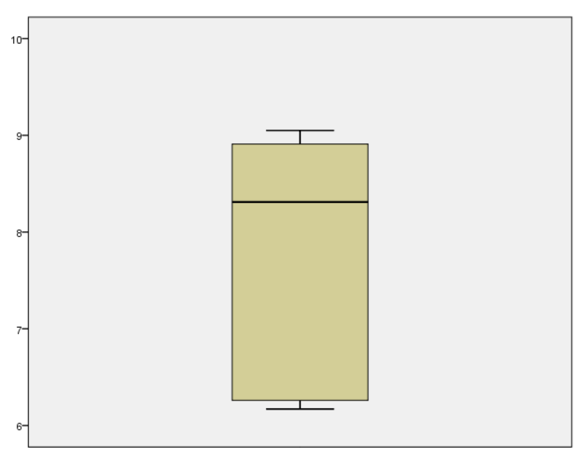


Figure B.5: CA at MTH3 region for healthy young participants

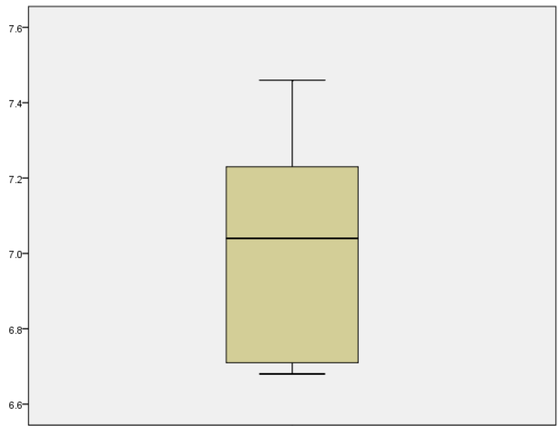


Figure B.6: CA at MTH4 region for healthy young participants

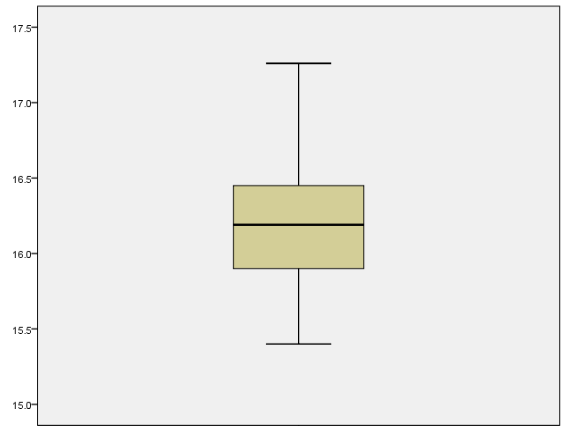


Figure B.7: CA at MTH5 region for healthy young participants

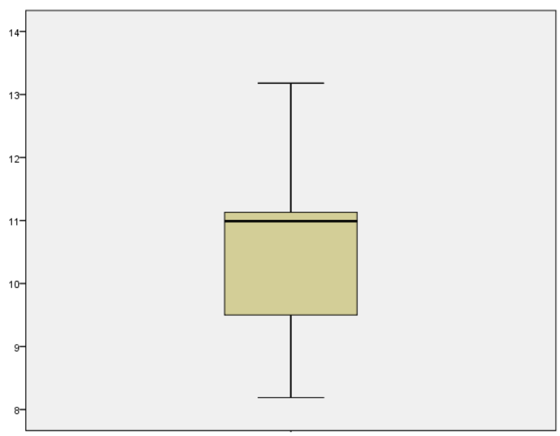


Figure B.8: CA at hallux region for healthy young participants

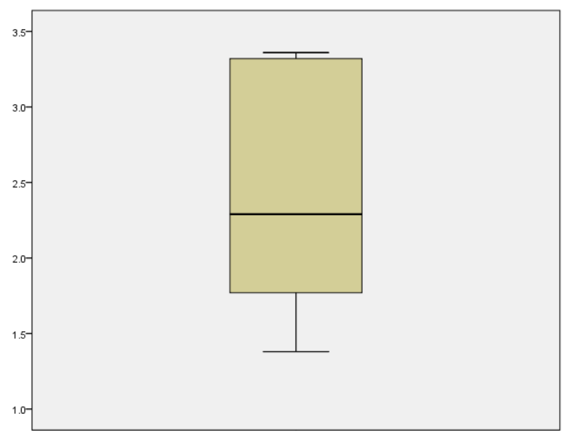


Figure B.9: CA at 2nd toe region for healthy young participants

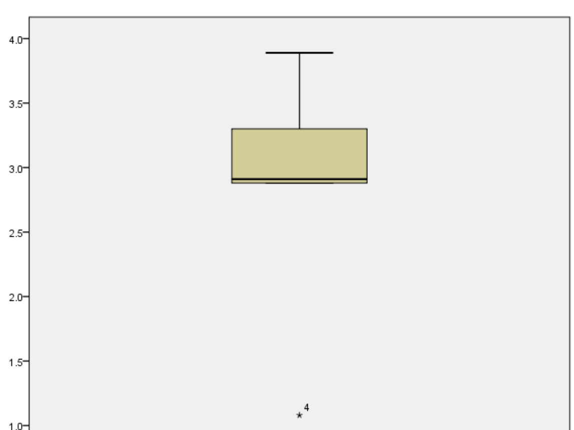


Figure B.10: CA at 3-5th toes region for healthy young participants

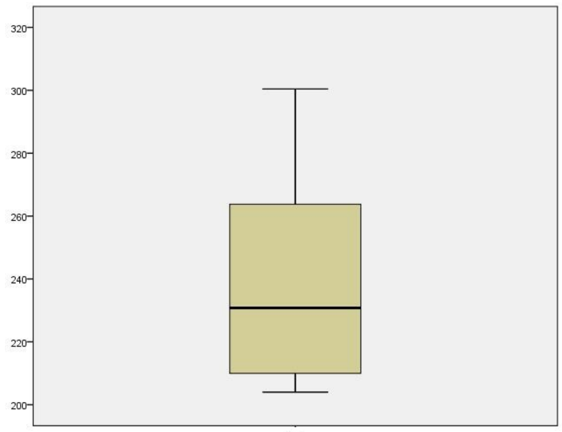


Figure B.11: MeF at heel region for healthy young participants

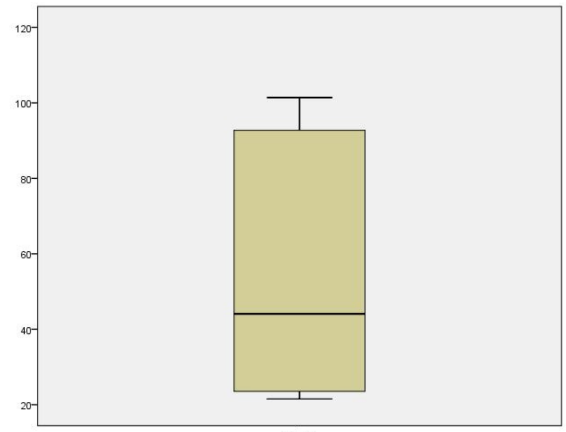


Figure B.12: MeF at midfoot region for healthy young participants

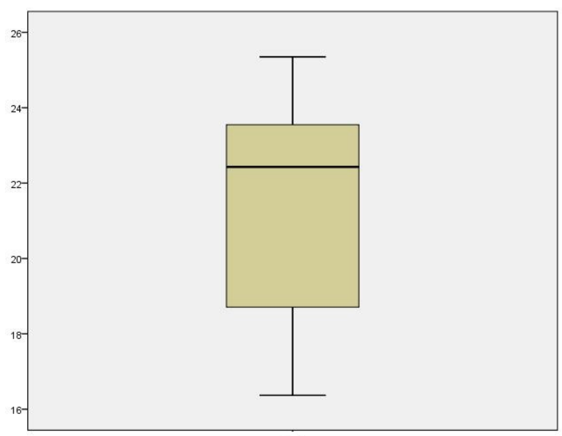


Figure B.13: MeF at MTH1 region for healthy young participants

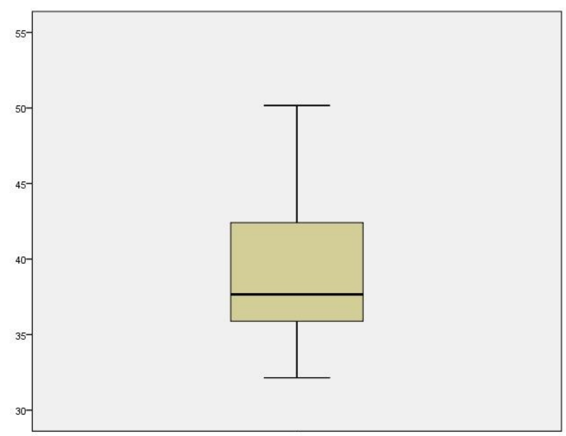


Figure B.14: MeF at MTH2 region for healthy young participants

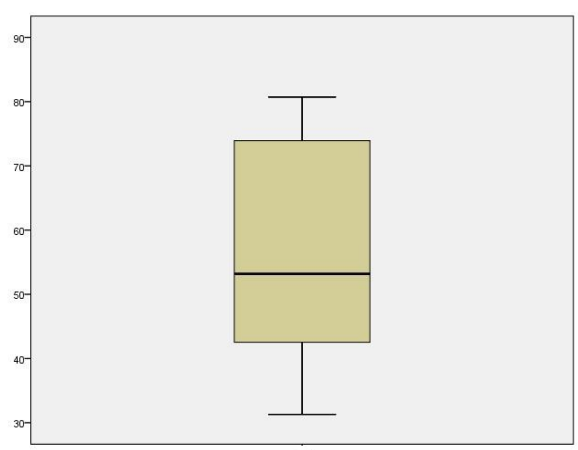


Figure B.15: MeF at MTH3 region for healthy young participants

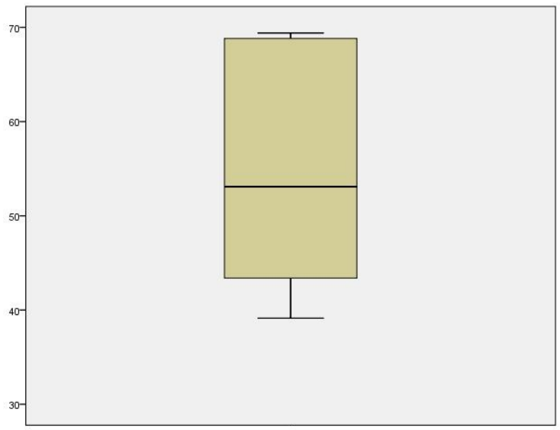


Figure B.16: MeF at MTH4 region for healthy young participants

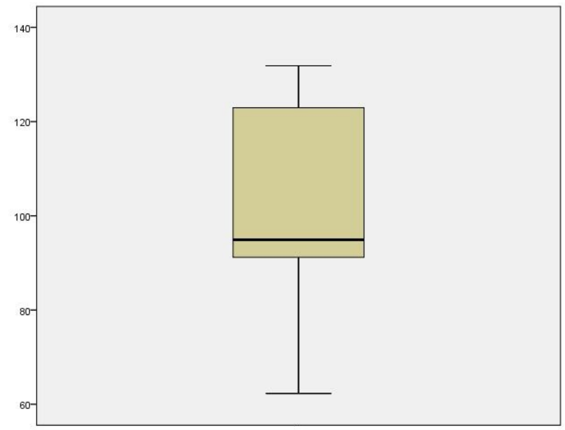


Figure B.17: MeF at MTH5 region for healthy young participants

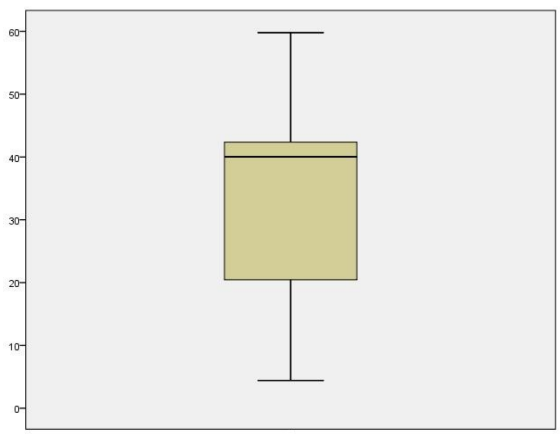


Figure B.18: MeF at hallux region for healthy young participants

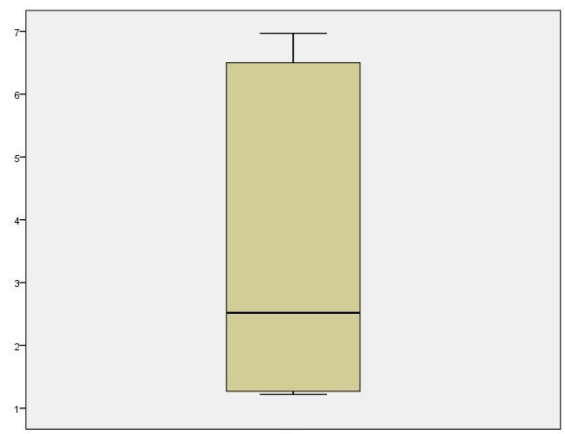


Figure B.19: MeF at 2nd toe region for healthy young participants

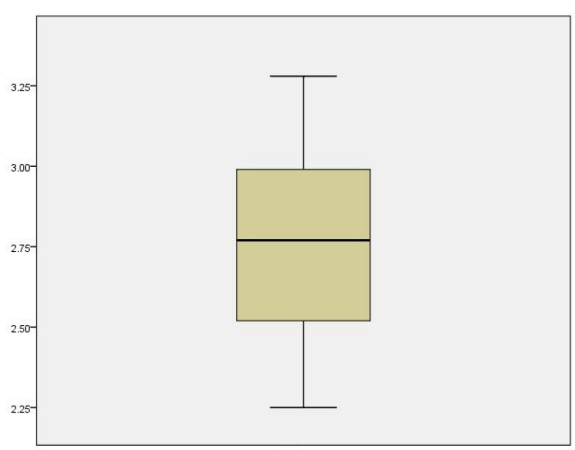


Figure B.20: MeF at 3-5th toes region for healthy young participants

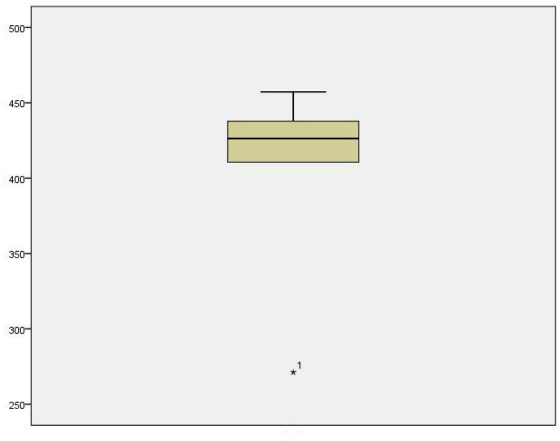


Figure B.21: PP at heel region for healthy young participants

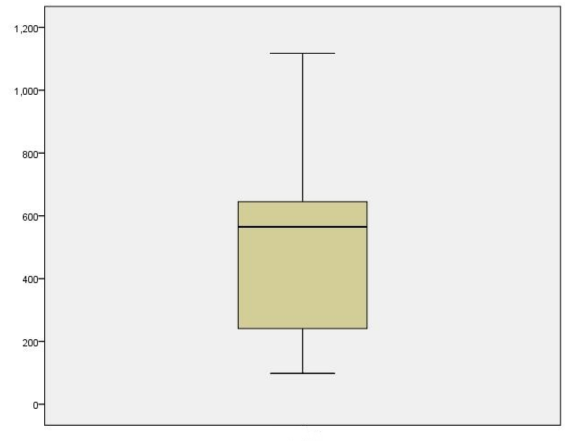


Figure B.22: PP at midfoot region for healthy young participants

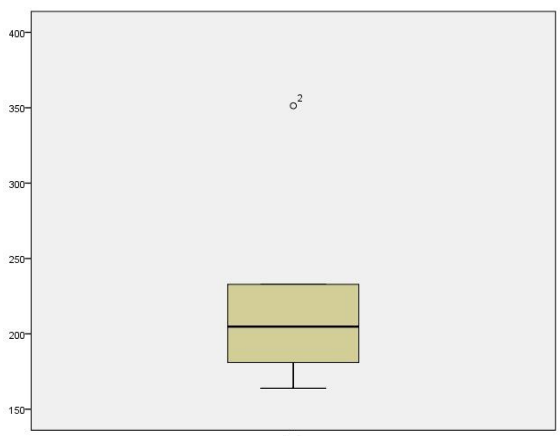


Figure B.23: PP at MTH1 region for healthy young participants

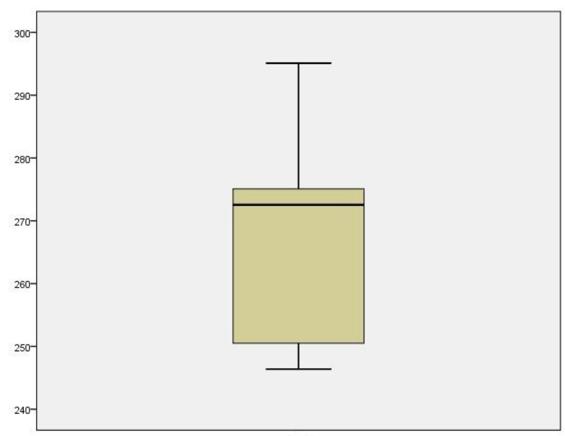


Figure B.24: PP at MTH2 region for healthy young participants

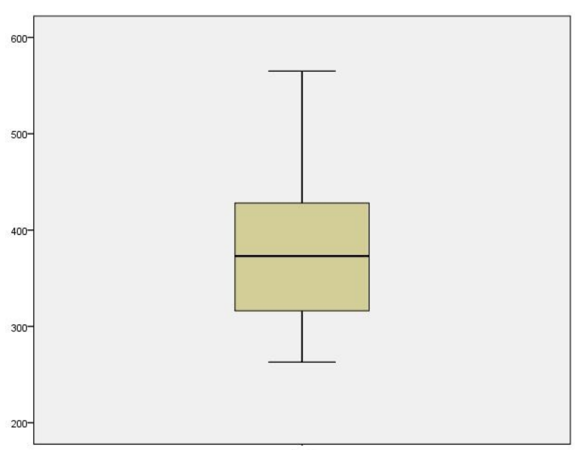


Figure B.25: PP at MTH3 region for healthy young participants

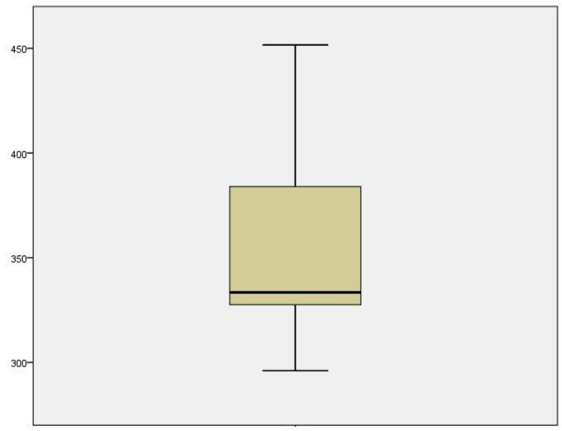


Figure B.26: PP at MTH4 region for healthy young participants

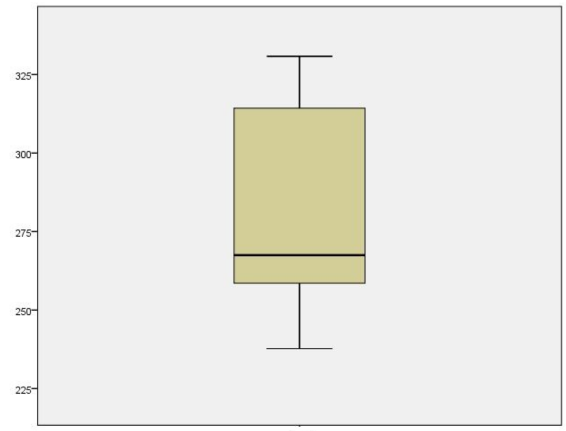


Figure B.27: PP at MTH5 region for healthy young participants

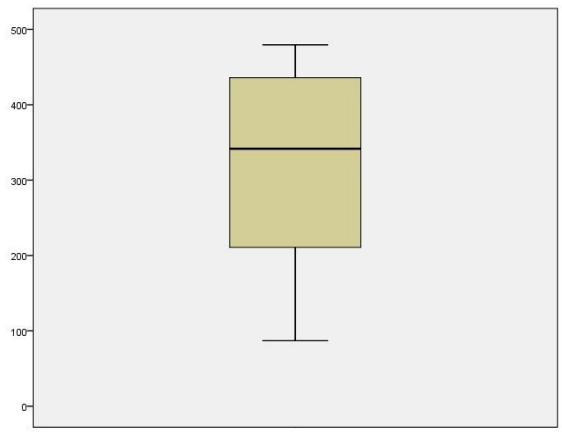


Figure B.28: PP at hallux region for healthy young participants

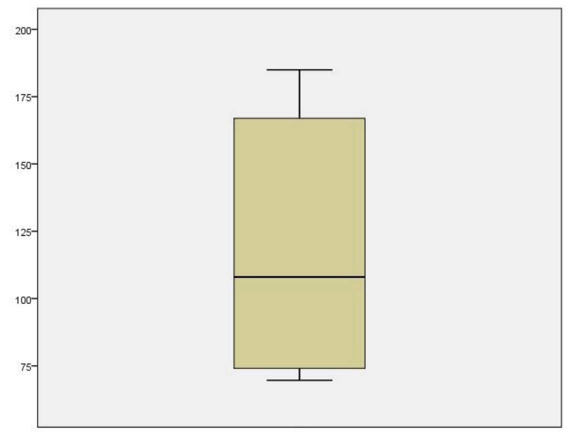


Figure B.29: PP at 2nd toe region for healthy young participants

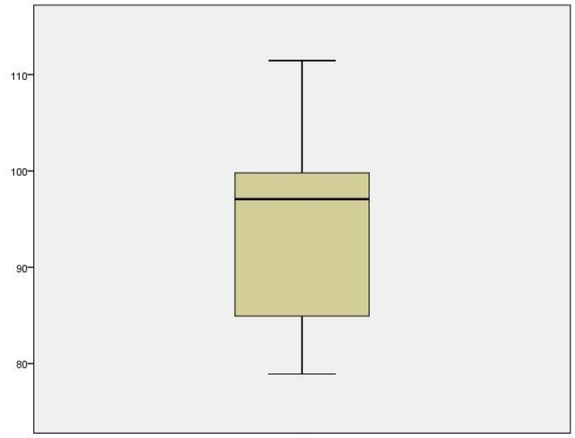


Figure B.30: PP at 3-5th toes region for healthy young participants

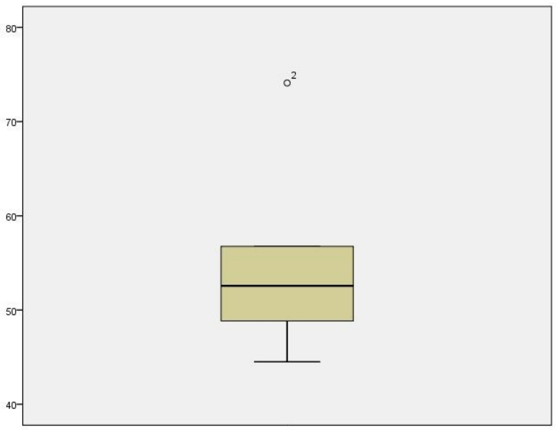


Figure B.31: PTI at heel region for healthy young participants

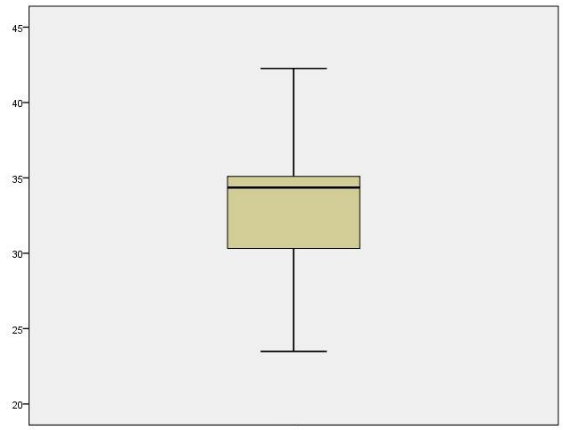


Figure B.32: PTI at midfoot region for healthy young participants

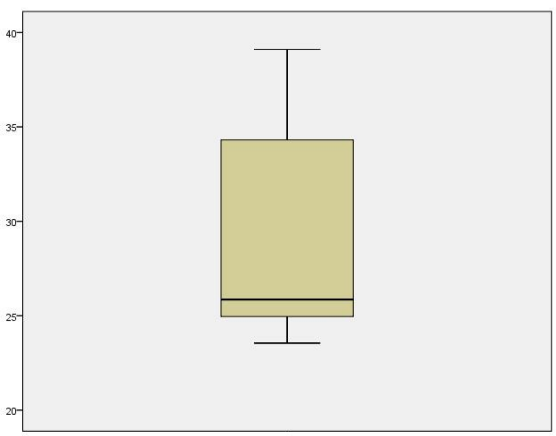


Figure B.33: PTI at MTH1 region for healthy young participants

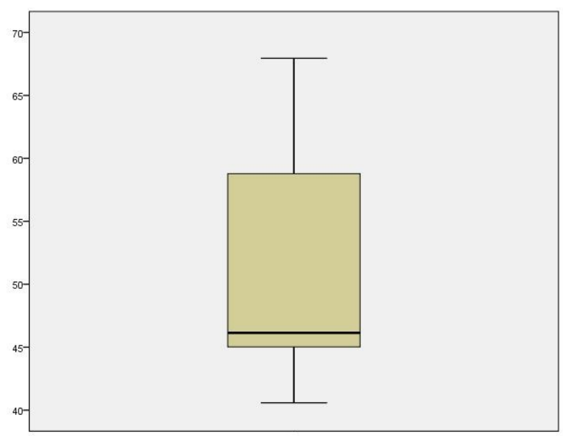


Figure B.34: PTI at MTH2 region for healthy young participants

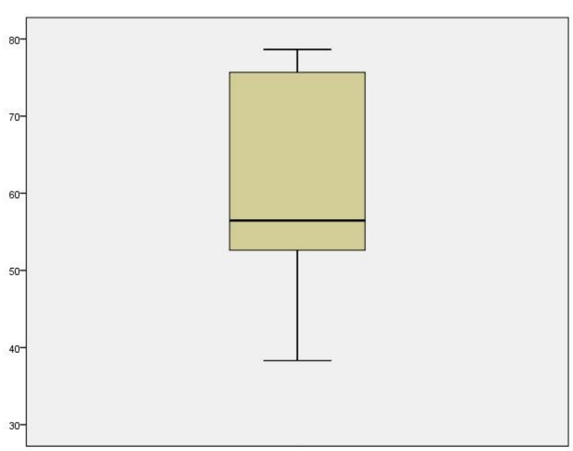


Figure B.35: PTI at MTH3 region for healthy young participants

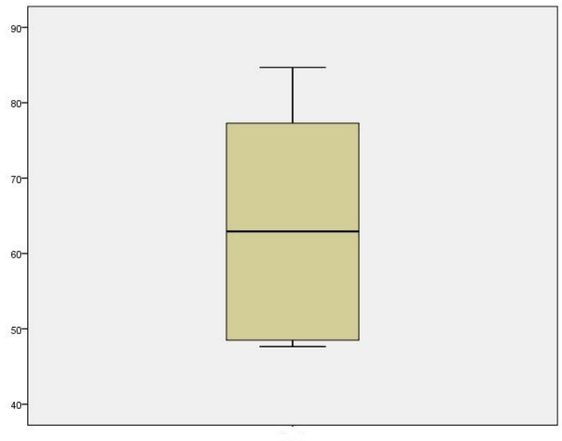


Figure B.36: PTI at MTH4 region for healthy young participants

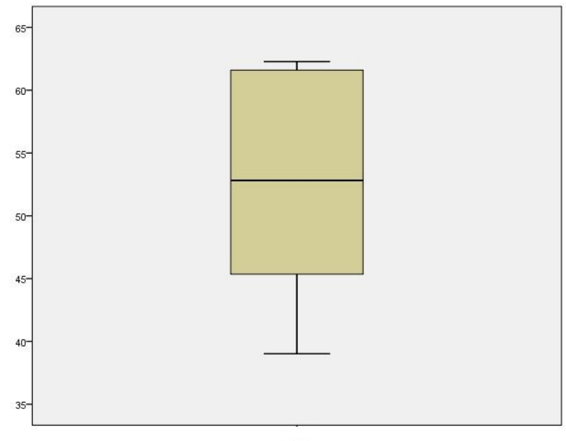


Figure B.37: PTI at MTH5 region for healthy young participants

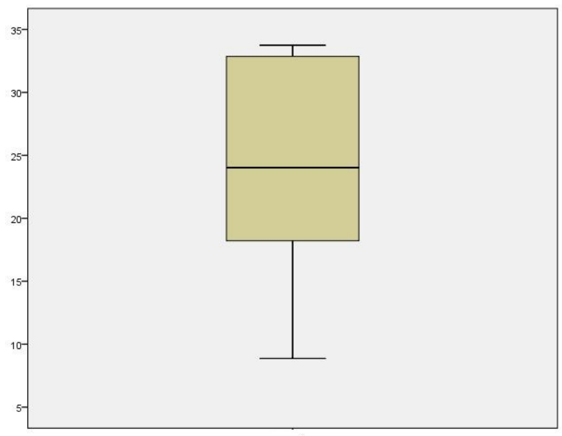


Figure B.38: PTI at hallux region for healthy young participants

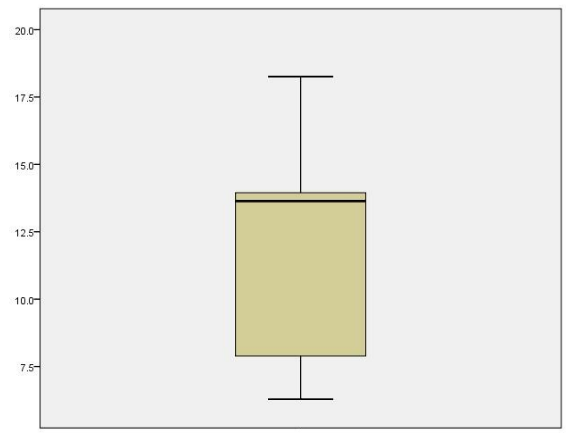


Figure B.39: PTI at 2nd toe region for healthy young participants

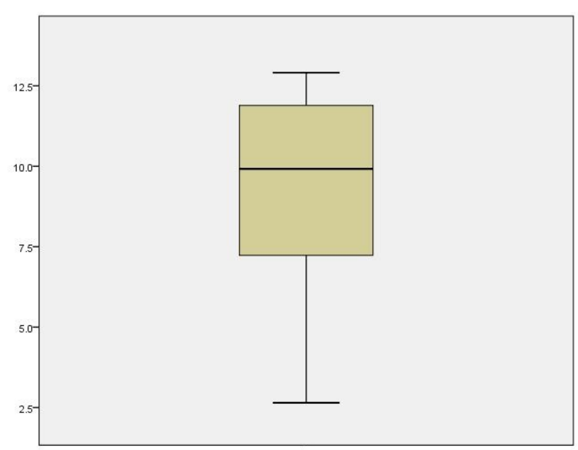


Figure B.40: PTI at 3-5th toes region for healthy young participants

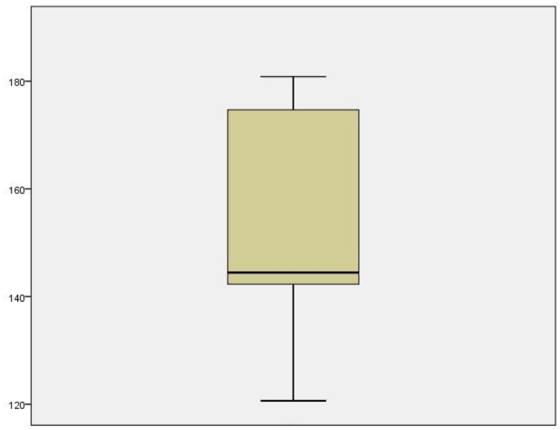


Figure B.41: FTI at heel region for healthy young participants

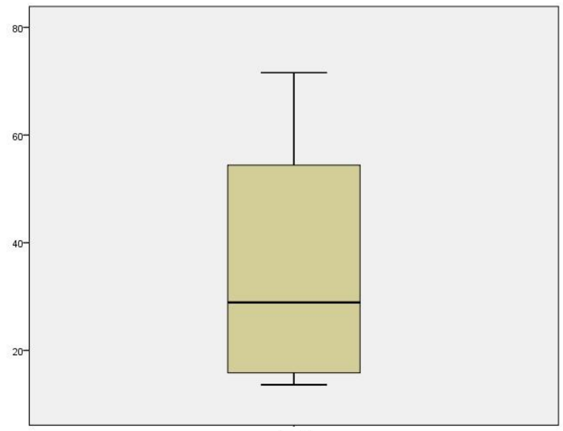


Figure B.42: FTI at midfoot region for healthy young participants

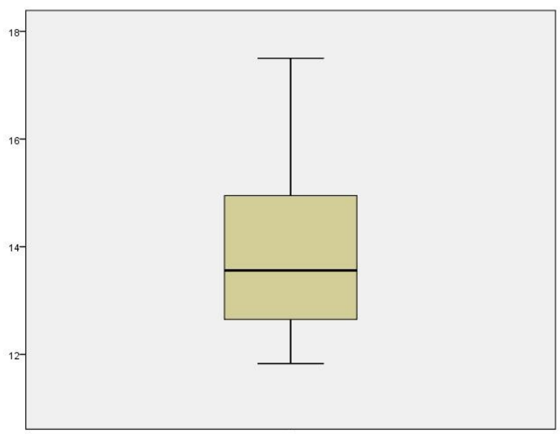


Figure B.43: FTI at MTH1 region for healthy young participants

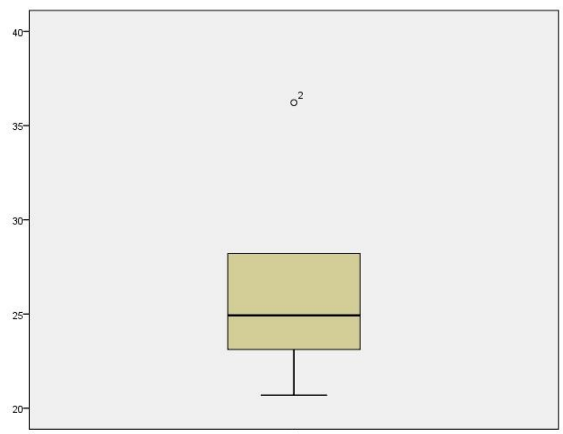


Figure B.44: FTI at MTH2 region for healthy young participants

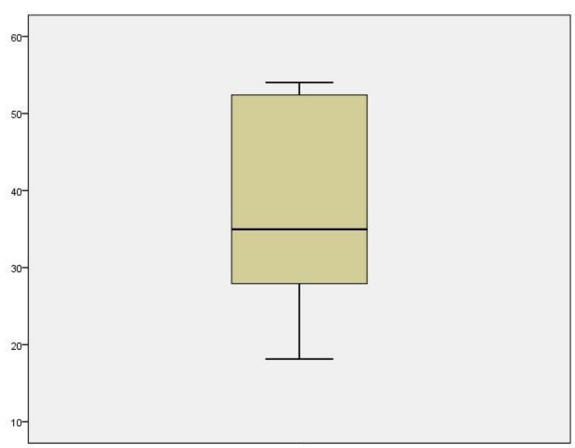


Figure B.45: FTI at MTH3 region for healthy young participants

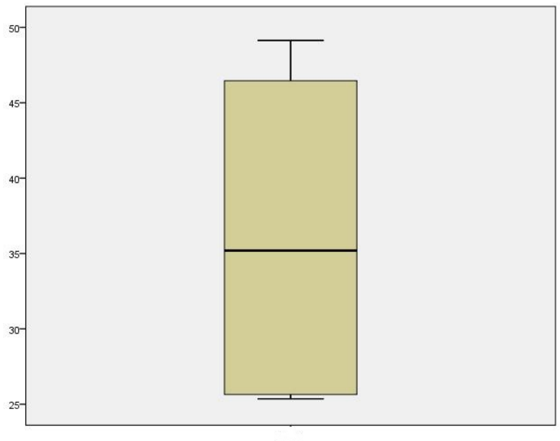


Figure B.46: FTI at MTH4 region for healthy young participants

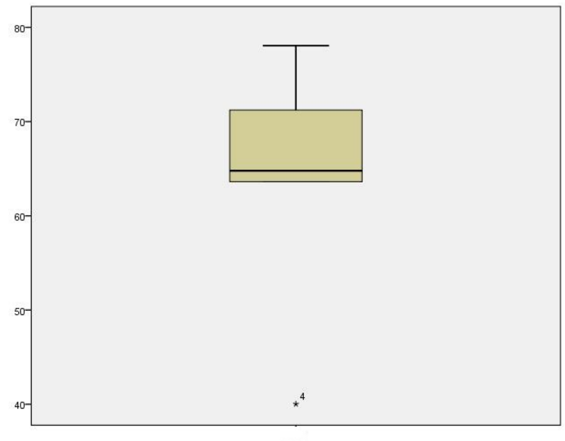


Figure B.47: FTI at MTH5 region for healthy young participants

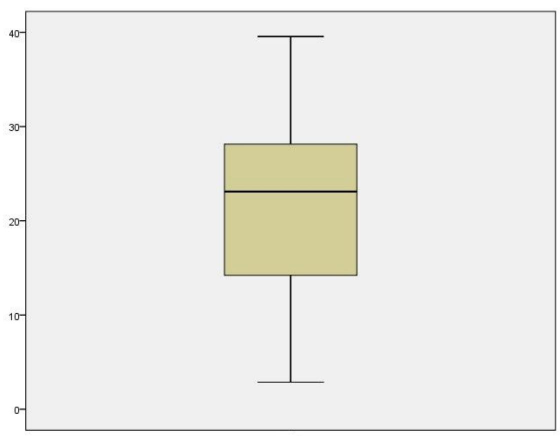


Figure B.48: FTI at hallux region for healthy young participants

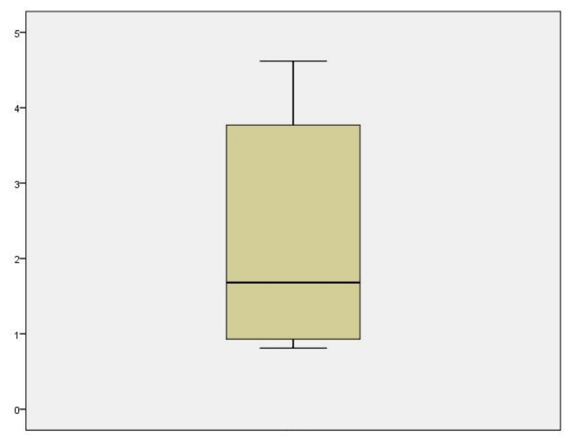


Figure B.49: FTI at 2nd toe region for healthy young participants

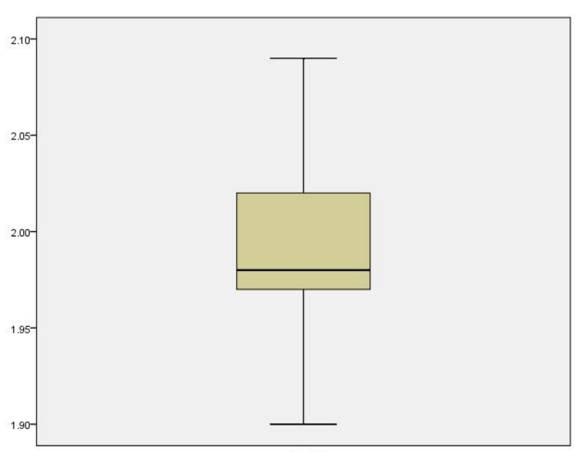


Figure B.50: FTI at 3-5th toes region for healthy young participants

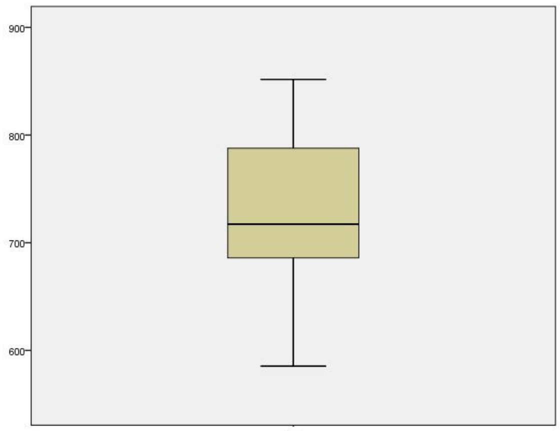


Figure B.51: MF at heel region for healthy young participants

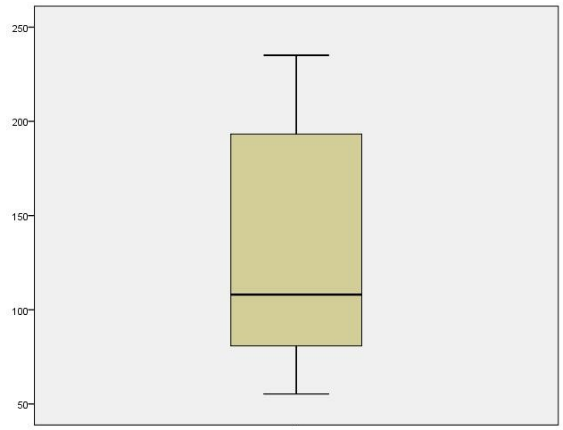


Figure B.52: MF at midfoot region for healthy young participants

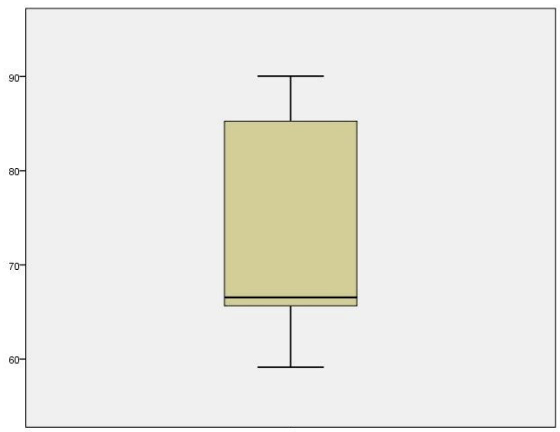


Figure B.53: MF at MTH1 region for healthy young participants

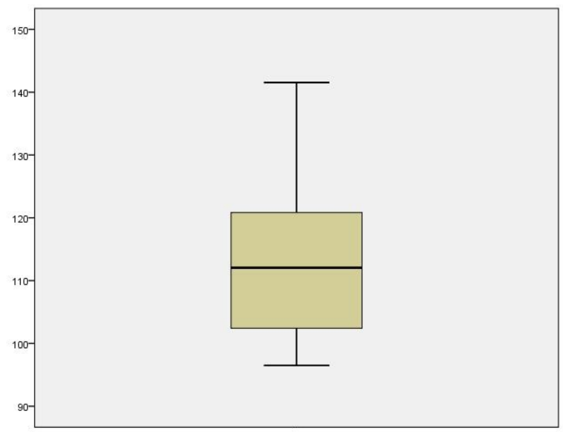


Figure B.54: MF at MTH2 region for healthy young participants

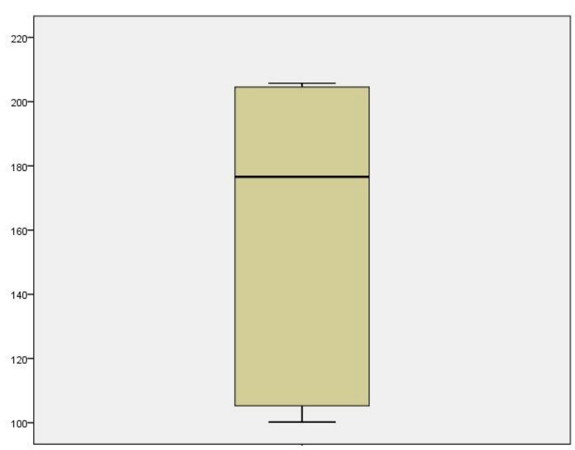


Figure B.55: MF at MTH3 region for healthy young participants

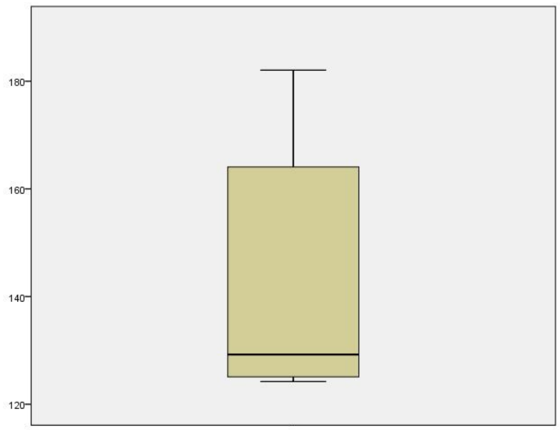


Figure B.56: MF at MTH4 region for healthy young participants

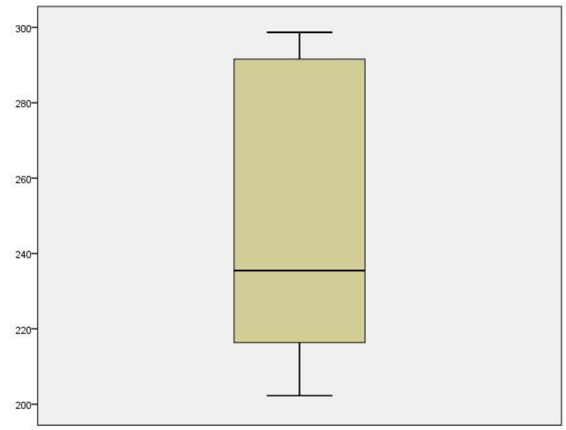


Figure B.57: MF at MTH5 region for healthy young participants

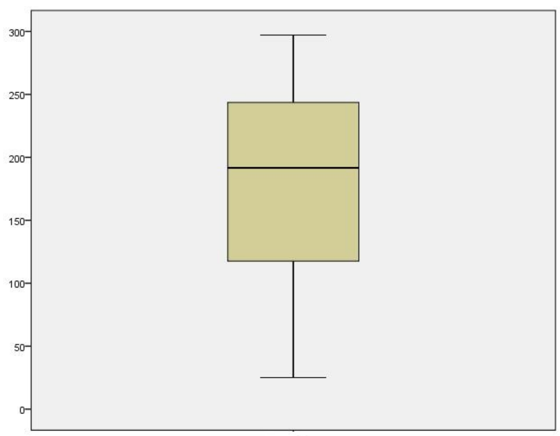


Figure B.58: MF at hallux region for healthy young participants

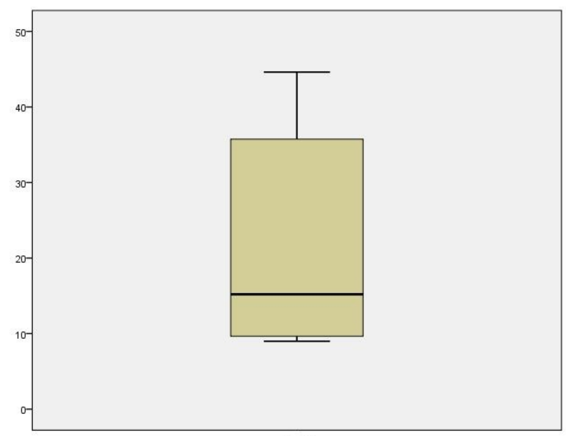


Figure B.59: MF at 2nd toe region for healthy young participants

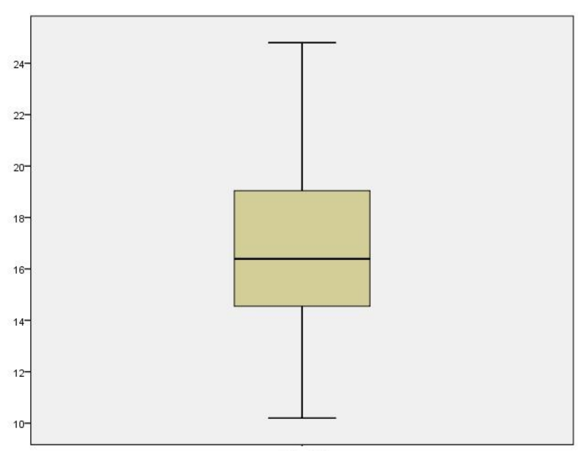


Figure B.60: MF at 3-5th toes region for healthy young participants

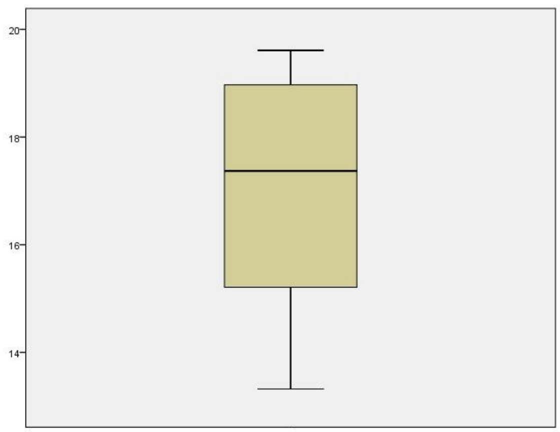


Figure B.61: MeA at heel region for healthy young participants

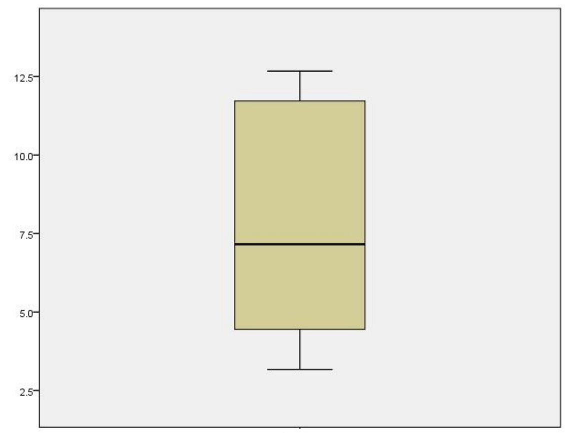


Figure B.62: MeA at midfoot region for healthy young participants

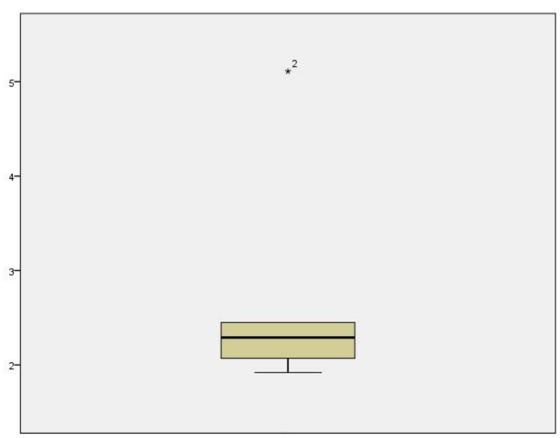


Figure B.63: MeA at MTH1 region for healthy young participants

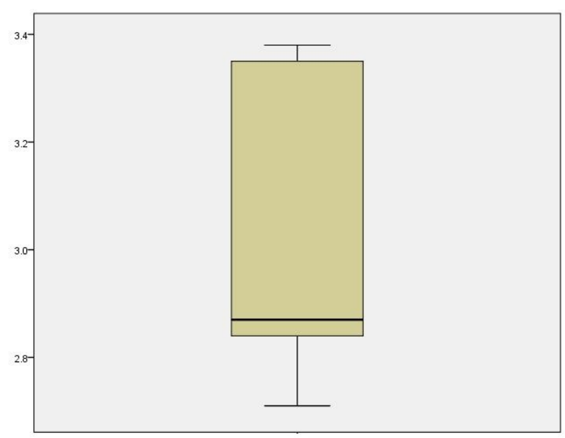


Figure B.64: MeA at MTH2 region for healthy young participants

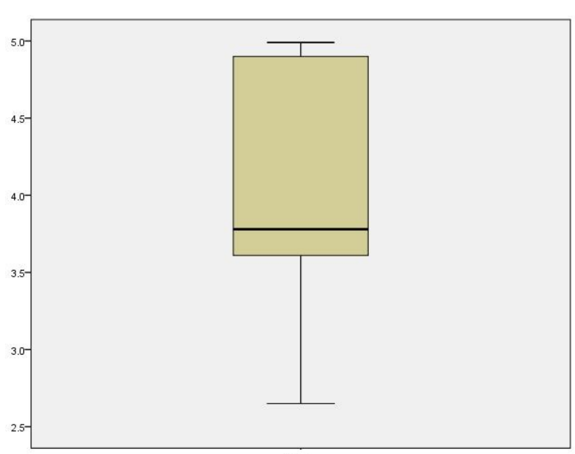


Figure B.65: MeA at MTH3 region for healthy young participants

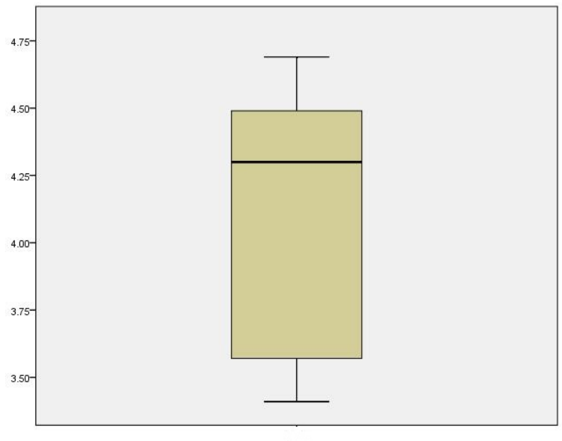


Figure B.66: MeA at MTH4 region for healthy young participants

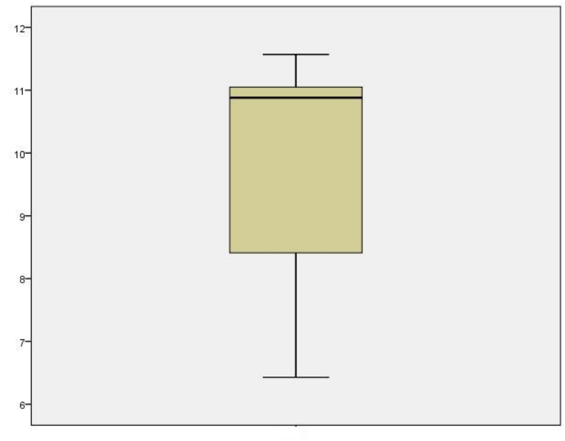


Figure B.67: MeA at MTH5 region for healthy young participants

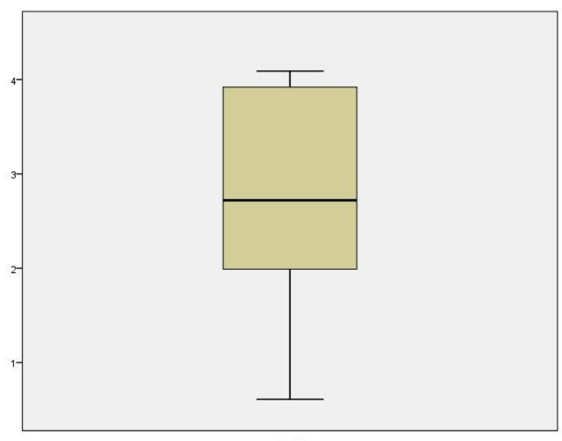


Figure B.68: MeA at hallux region for healthy young participants

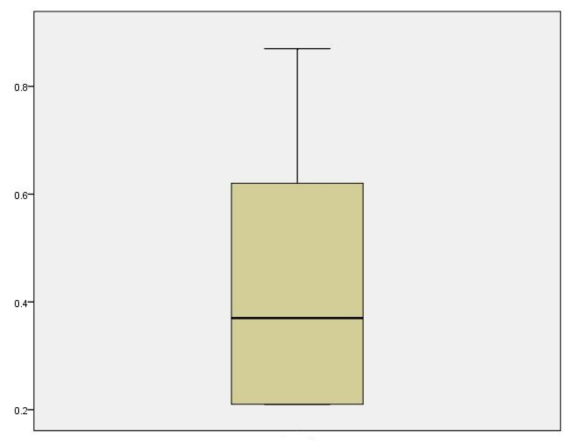


Figure B.69: MeA at 2nd toe region for healthy young participants

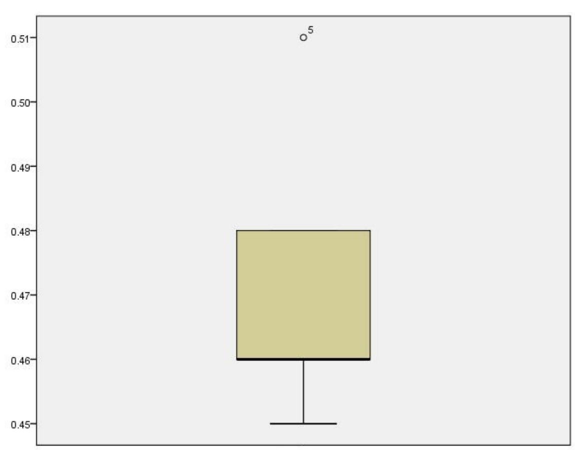


Figure B.70: MF at 3-5th toes region for healthy young participants

# Appendix C

# Results of Distribution tests and Outlier Detection: Healthy Older Adults

## C.1 Shapiro-Wilks test

This section includes the results of Shapiro-Wilks tests of 20 parameters, i.e. MF, CA, PP, PTI and FTI from the regions of the whole foot, rearfoot, midfoot and forefoot, studied of the healthy older adults group.

Table C.1: Shapiro-Wilk test for MF of older participants

| masks | **Whole Foot** | **Rearfoot** | **Midfoot** | **Forefoot** |
|---|---|---|---|---|
| **Sig.** | 0.912 | 0.894 | 0.749 | 0.841 |

Table C.2: Shapiro-Wilk test for CA of older participants

| masks | **Whole Foot** | **Rearfoot** | **Midfoot** | **Forefoot** |
|---|---|---|---|---|
| **Sig.** | 0.297 | 0.042 | 0.271 | 0.396 |

Table C.3: Shapiro-Wilk test for PP of older participants

| masks | **Whole Foot** | **Rearfoot** | **Midfoot** | **Forefoot** |
|---|---|---|---|---|
| **Sig.** | 0.994 | 0.868 | 0.592 | 0.613 |

Table C.4: Shapiro-Wilk test for PTI of older participants

| masks | **Whole Foot** | **Rearfoot** | **Midfoot** | **Forefoot** |
|---|---|---|---|---|
| **Sig.** | 0.060 | 0.210 | 0.851 | 0.098 |

Table C.5: Shapiro-Wilk test for FTI of older participants

| masks | **Whole Foot** | **Rearfoot** | **Midfoot** | **Forefoot** |
|---|---|---|---|---|
| **Sig.** | 0.887 | 0.509 | 0.788 | 0.660 |

## C.2 Box-plots

This section includes the results of outlier detection of 20 parameters, i.e. MF, CA, PP, PTI and FTI from the regions of the whole foot, rearfoot, midfoot and forefoot, studied of the healthy older adults group.

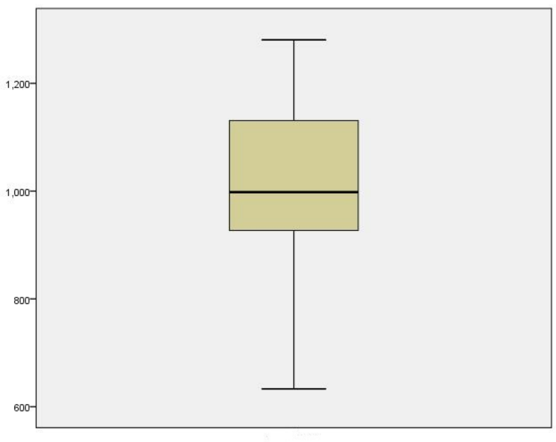


Figure C.1: MF at whole foot for older participants

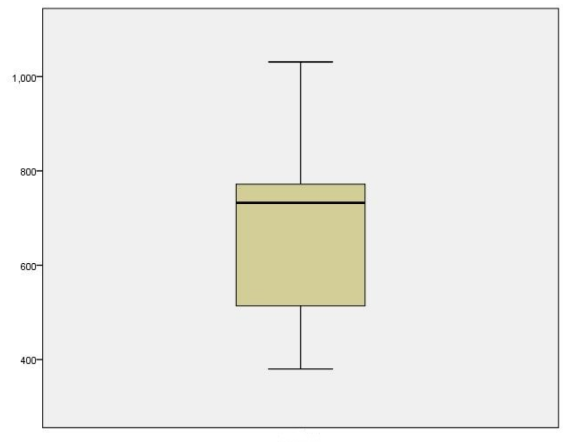


Figure C.2: MF at rearfoot region for older participants

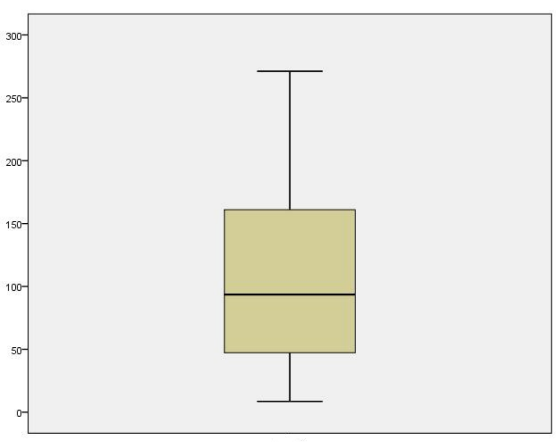


Figure C.3: MF at midfoot region for older participants

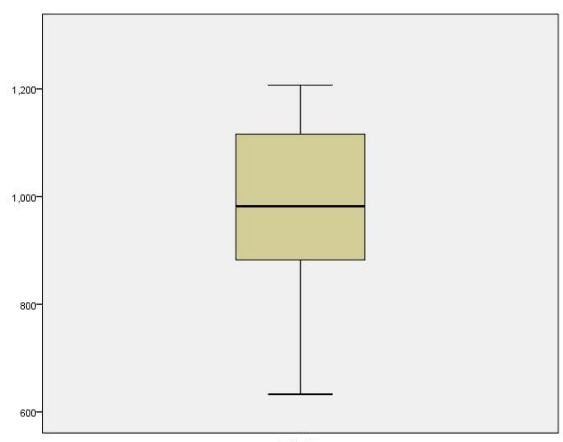


Figure C.4: MF at forefoot region for older participants

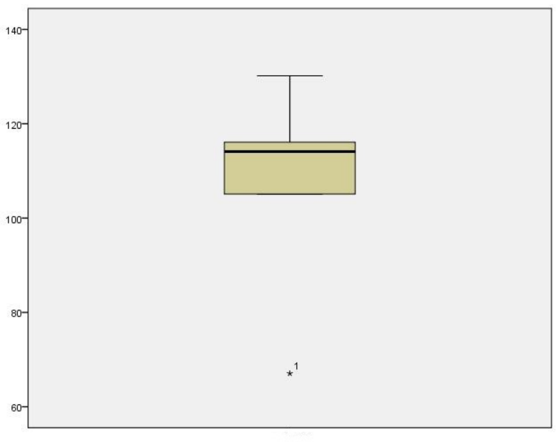


Figure C.5: CA at whole foot for older participants

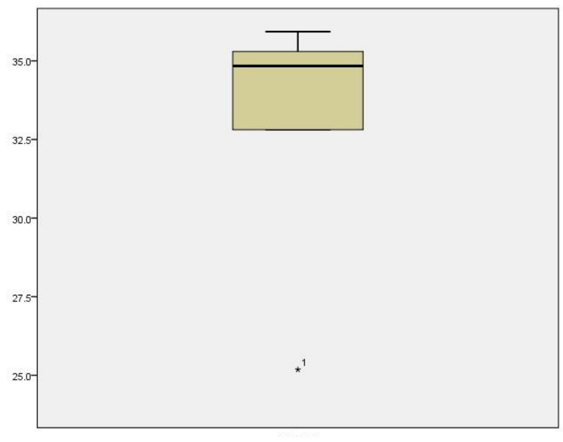


Figure C.6: CA at rearfoot region for older participants

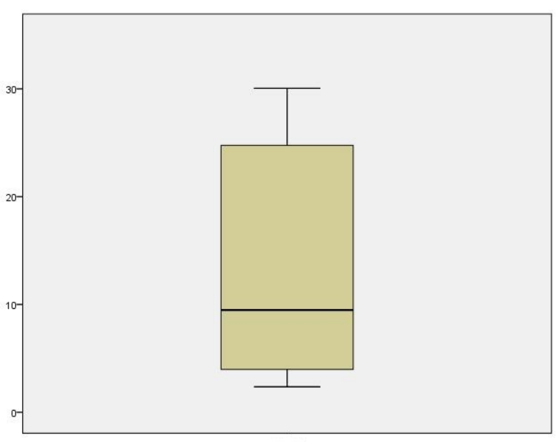


Figure C.7: CA at midfoot region for older participants

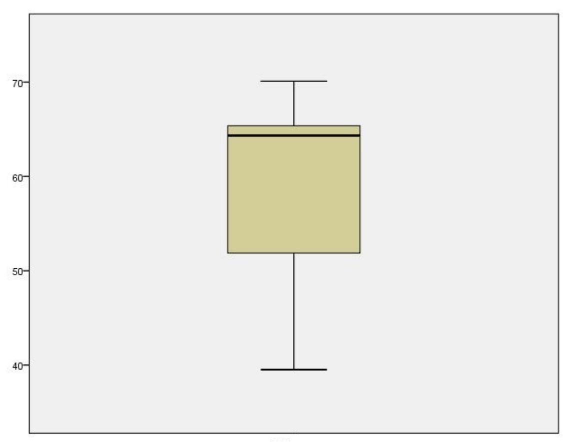


Figure C.8: CA at forefoot region for older participants

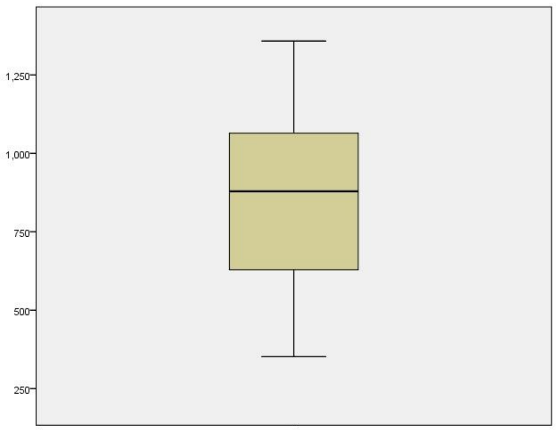


Figure C.9: PP at whole foot for older participants

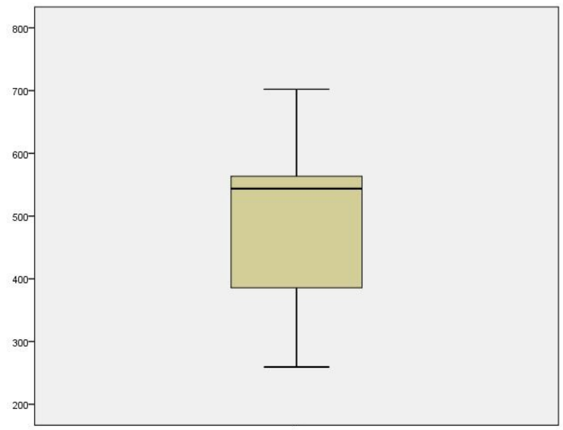


Figure C.10: PP at rearfoot region for older participants

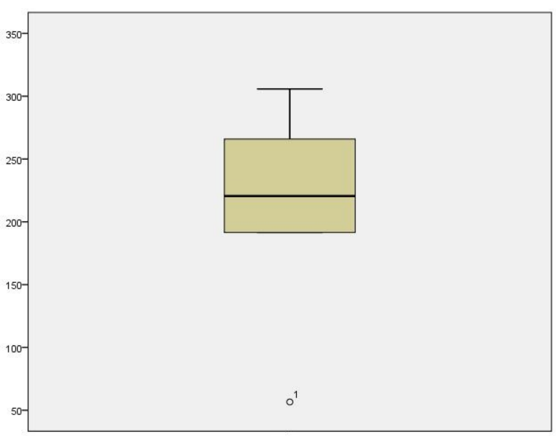


Figure C.11: PP at midfoot region for older participants

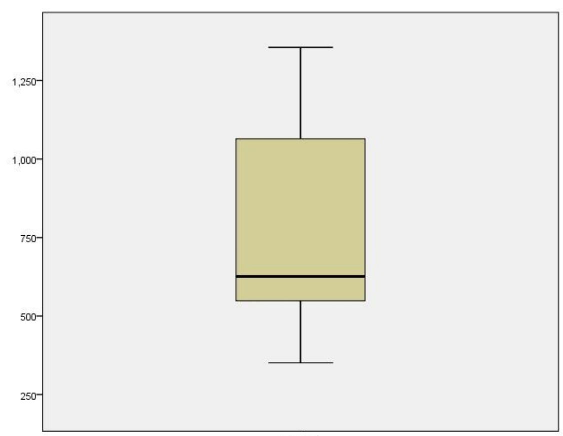


Figure C.12: PP at forefoot region for older participants

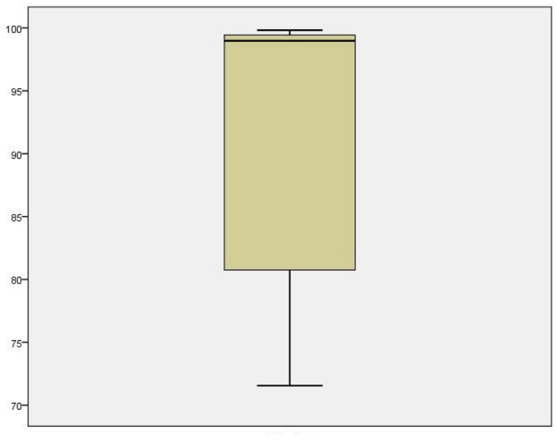


Figure C.13: PTI at whole foot for older participants

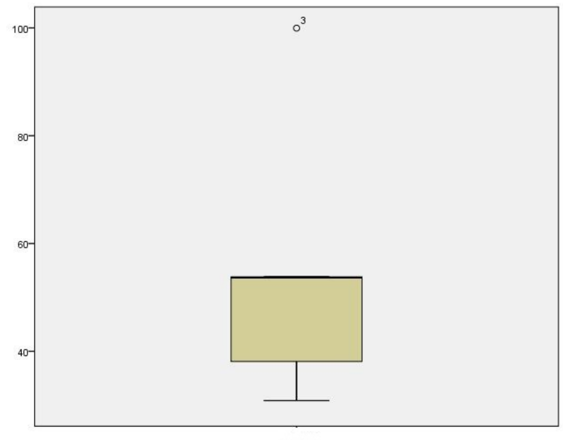


Figure C.14: PTI at rearfoot region for older participants

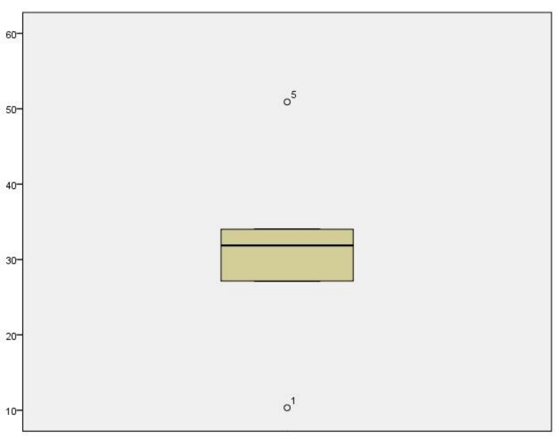


Figure C.15: PTI at midfoot region for older participants

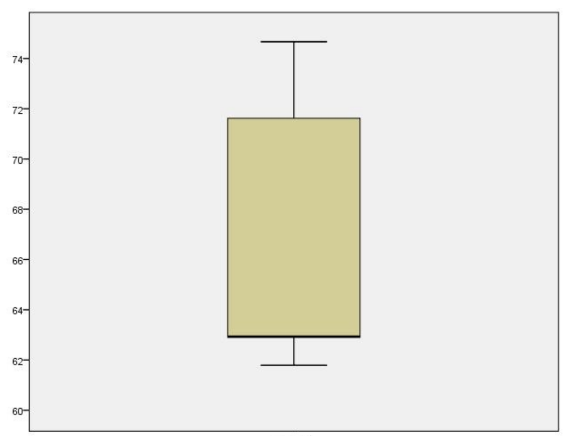


Figure C.16: PTI at forefoot region for older participants

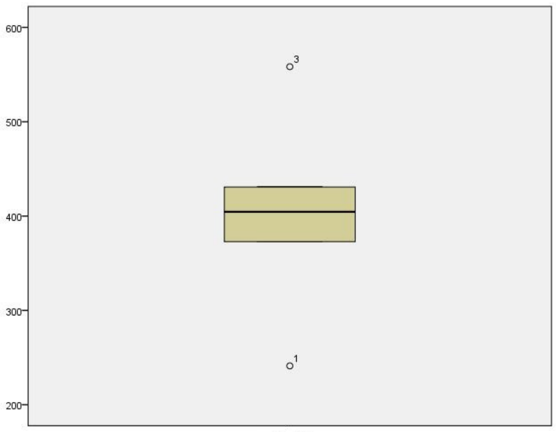


Figure C.17: FTI at whole foot for older participants

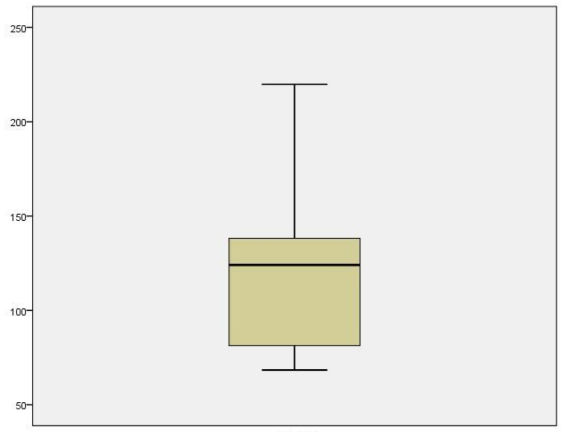


Figure C.18: FTI at rearfoot region for older participants

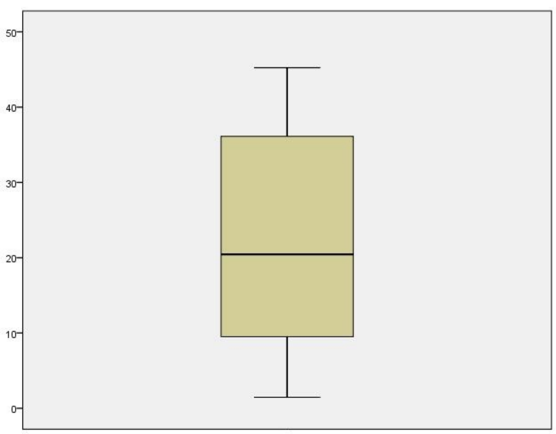


Figure C.19: FTI at midfoot region for older participants

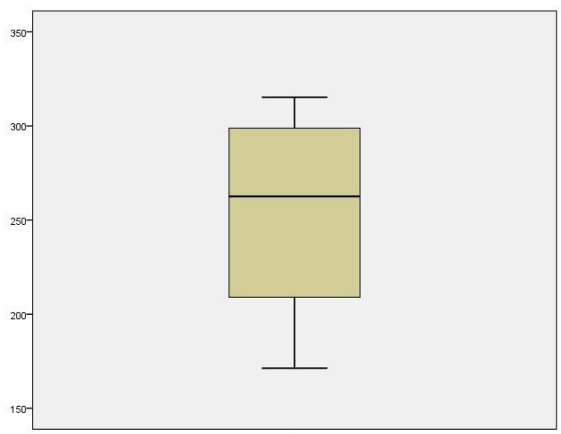


Figure C.20: FTI at forefoot region for older participants

# Appendix D

# Results of Distribution tests and Outlier Detection: Obese Adults

## D.1 Shapiro-Wilks test

This section includes the results of Shapiro-Wilks tests of 18 parameters, i.e. MF, CA and PP, from the regions of the whole foot, heel, midfoot, forefoot, hallux and toes, studied of the healthy obese adults group.

Table D.1: Shapiro-Wilk test for MF of obese participants

| masks | **Whole Foot** | **Heel** | **Midfoot** | **Forefoot** | **Hallux** | **Toes** |
|---|---|---|---|---|---|---|
| **Sig.** | 0.831 | 0.431 | 0.154 | 0.449 | 0.465 | 0.237 |

Table D.2: Shapiro-Wilk test for CA of obese participants

| masks | **Whole Foot** | **Heel** | **Midfoot** | **Forefoot** | **Hallux** | **Toes** |
|---|---|---|---|---|---|---|
| **Sig.** | 0.804 | 0.607 | 0.793 | 0.176 | 0.720 | 0.425 |

Table D.3: Shapiro-Wilk test for PP of obese participants

| masks | **Whole Foot** | **Heel** | **Midfoot** | **Forefoot** | **Hallux** | **Toes** |
|---|---|---|---|---|---|---|
| **Sig.** | 0.708 | 0.896 | 0.646 | 0.735 | 0.666 | 0.926 |

## D.2 Box-plots

This section includes the results of outlier detection of 18 parameters, i.e. MF, CA and PP, from the regions of the whole foot, heel, midfoot, forefoot, hallux and toes, studied of the healthy obese adults group.

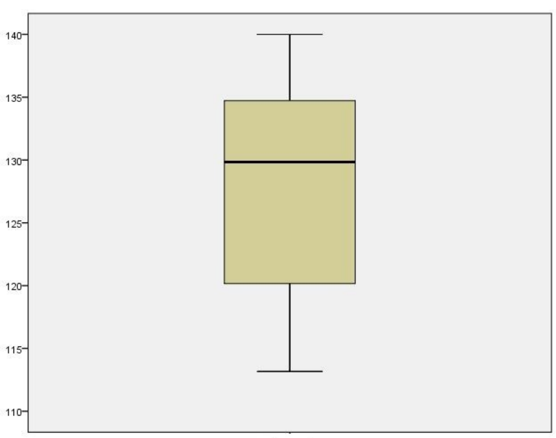


Figure D.1: MF at whole foot region for obese participants

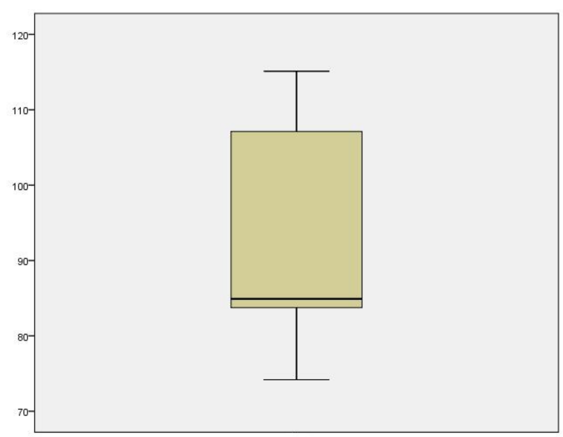


Figure D.2: MF at heel region for obese participants

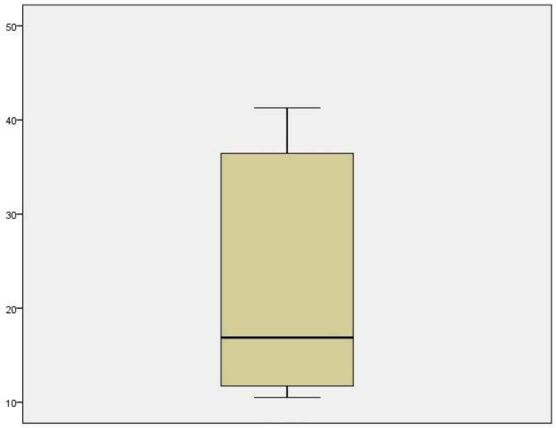


Figure D.3: MF at midfoot region for obese participants

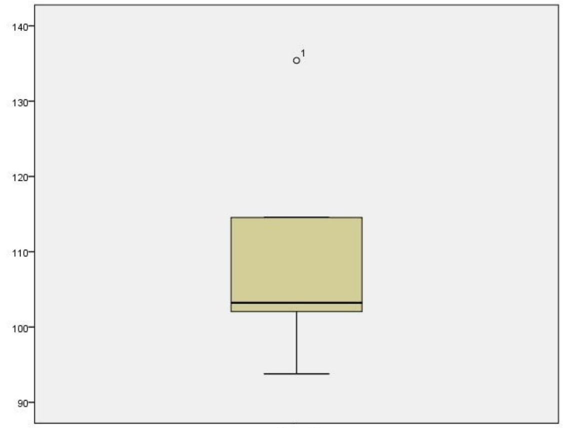


Figure D.4: MF at forefoot region for obese participants

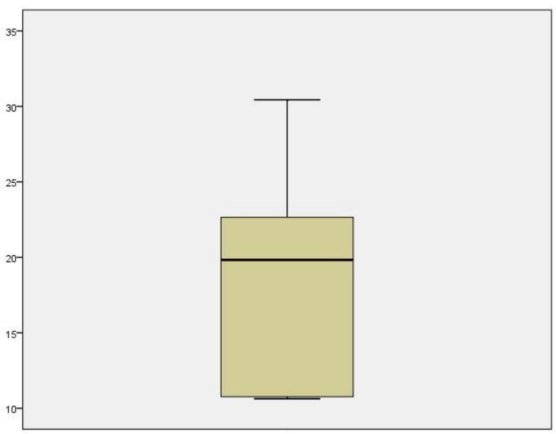


Figure D.5: MF at hallux region for obese participants

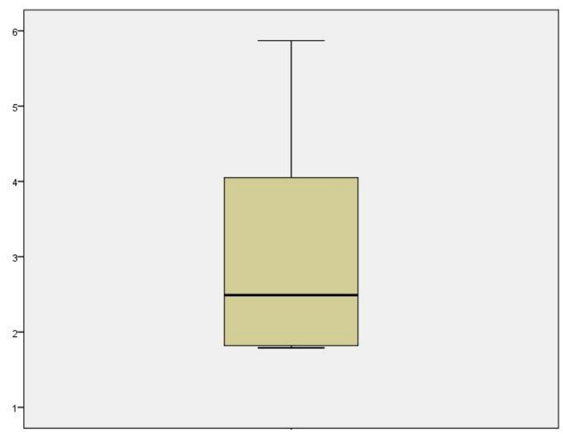


Figure D.6: MF at toes region for obese participants

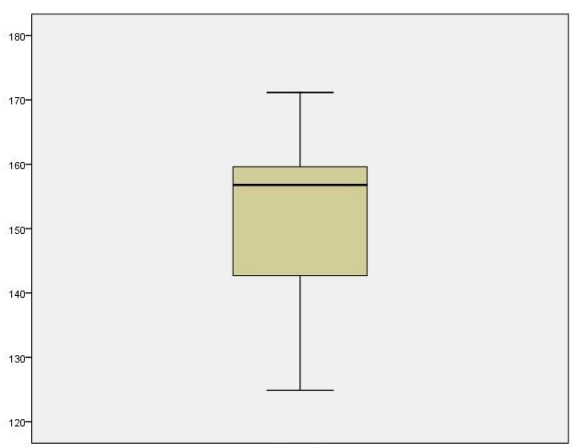


Figure D.7: CA at whole foot region for obese participants

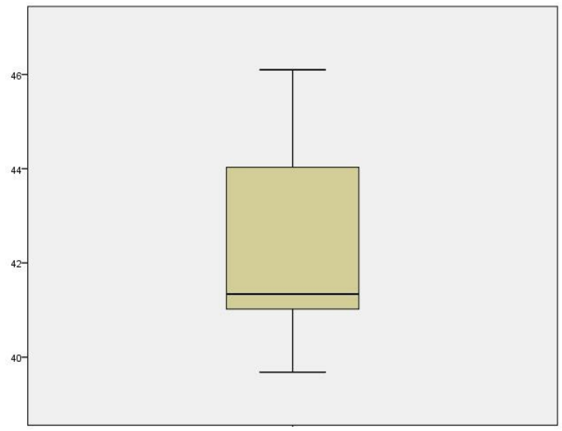


Figure D.8: CA at heel region for obese participants

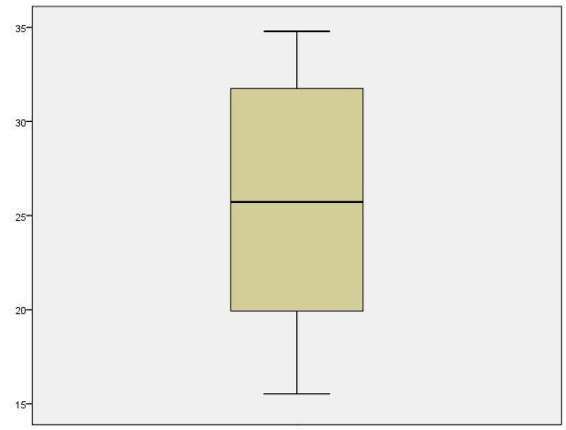


Figure D.9: CA at midfoot region for obese participants

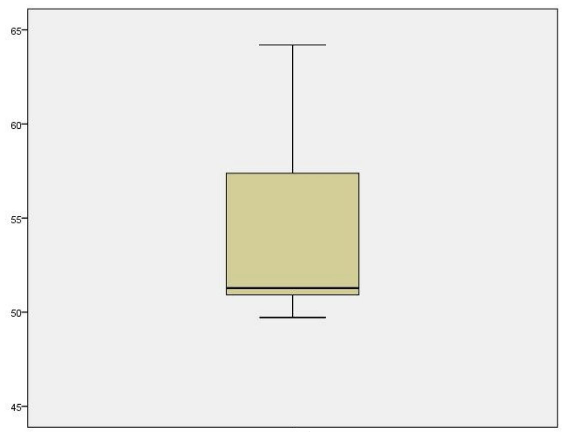


Figure D.10: CA at forefoot region for obese participants

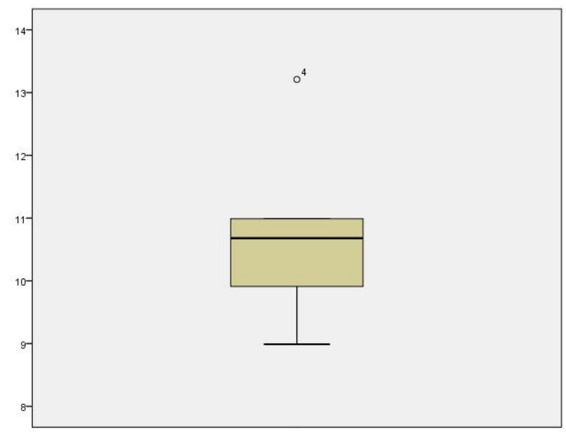


Figure D.11: CA at hallux region for obese participants

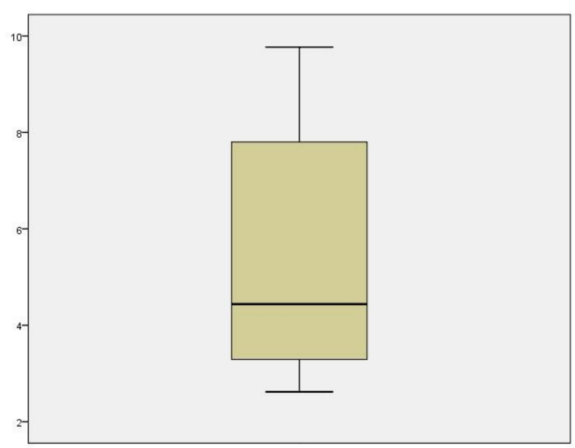


Figure D.12: CA at toes region for obese participants

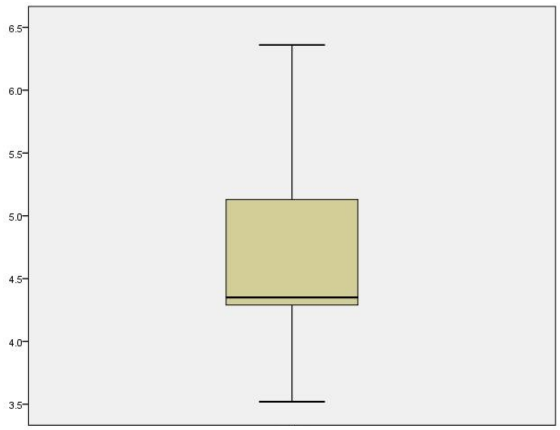


Figure D.13: PP at whole foot region for obese participants

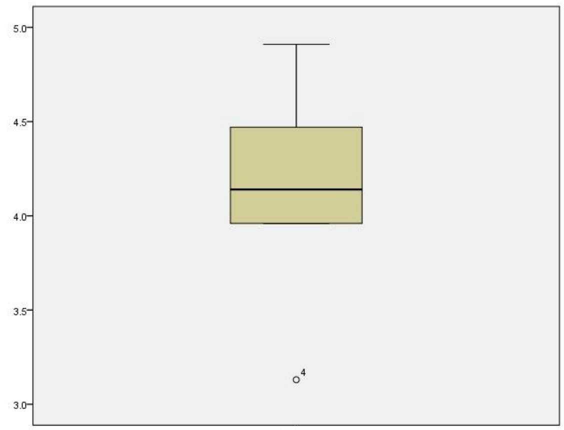


Figure D.14: PP at heel region for obese participants

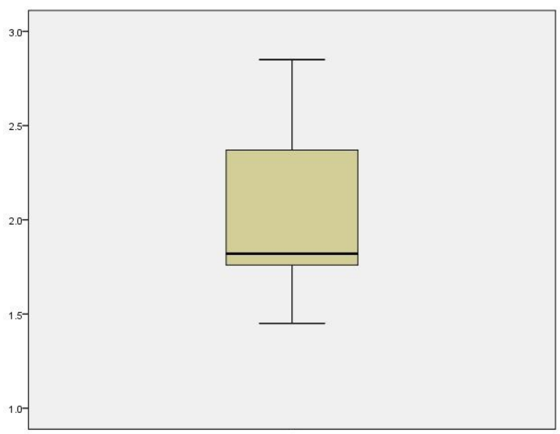


Figure D.15: PP at midfoot region for obese participants

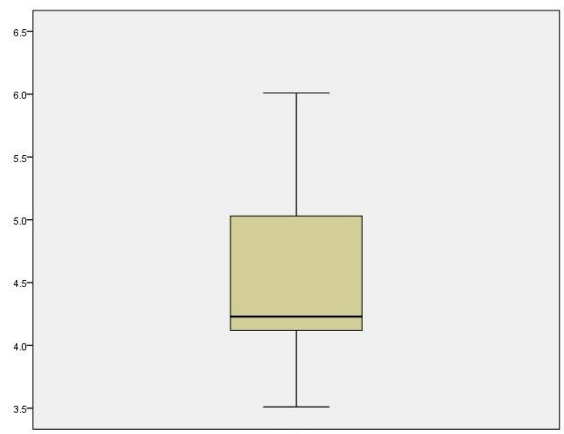


Figure D.16: PP at forefoot region for obese participants

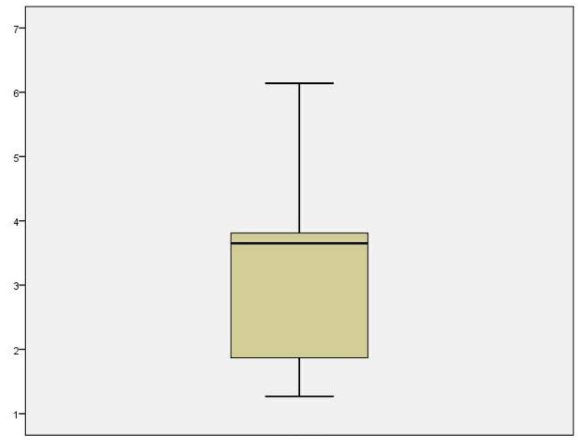


Figure D.17: PP at hallux region for obese participants

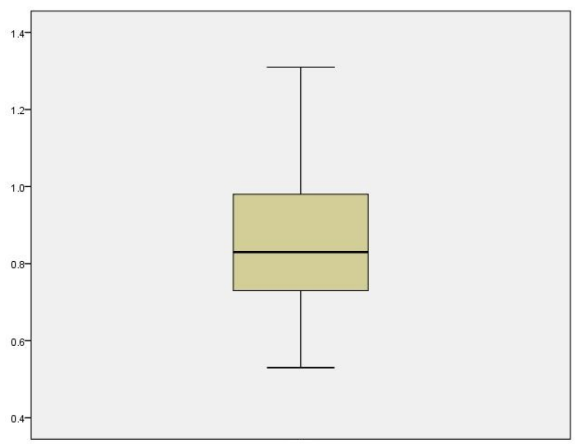


Figure D.18: PP at toes region for obese participants