PLANTAR PRESSURE IMAGE AND 3D GAIT PHASE IMAGE COMPARISON BETWEEN OLDER ADULTS AND ADULTS

A Thesis submitted by

Nibras Sabih Abbas, MEng

For the award of

Doctor of Philosophy

2021

DEDICATION

To

God who gave me the power

My beloved parents who prayed for me day and night

My husband, Samer and my sons, Yaser and Hani who consistently supported me

My brother Mohammed and my sisters (Narjis and Nawras) who have always encouraged me

This thesis is dedicated to you

ABSTRACT

Although gait disorders during the loading phase of gait are serious concerns associated with increasing age, relatively few studies have investigated gait characteristics in healthy older adult subjects and the change in their gait parameters compared to adult subjects. This research study evaluates the variation in plantar pressure patterns, using F-scan pressure sensor insoles, in adults who have not reached an elderly age stage with associated deterioration in their foot planter's health and function. The study showed major changes in plantar pressure distribution measurements that commonly occur with advancing age. The findings from this investigation can inform the design of custom-made insoles, which would prevent the development of several foot problems sustained by older people. The results revealed an increase in plantar pressure measurements for older adults under a number of foot regions. The mid-foot region was an exemption, which showed a decrease in these measurements for the older adults' group compared to the adults' group. Furthermore, the percentage of the averaged weight for each group, when analysing plantar pressure parameters, showed similar findings to those undertaken for the initially analysed data, discounting a small number of variations between the two groups participating in the study: older adults and adults.

Research has demonstrated that the ability to maintain body balance during walking is likely to decline due to weakness in the strength of ankle muscles in older people, particularly for the most hazardous events: slips and trips. Maintaining balance while moving can be affected by the gait task being performed. Previous studies have investigated plantar pressure patterns during different gait tasks: up slopes, down slopes, upstairs, and downstairs; however, greater risks were shown for slope walking than stair walking. There is a lack of standard dynamic measurements of plantar pressure patterns for healthy older adults while performing different walking tasks wearing pressure sensor insoles. Hence, the study investigated plantar pressure parameters while walking on level surfaces and uphill and downhill walking steps for a group of older adults. Higher contact pressure, peak pressure, force-time integral, and pressure-time integral measures, particularly at the whole foot, forefoot, and hallux regions, were located for uphill walking conditions compared to level walking. For a group of older adults, these measures were accompanied by a decrease in contact area values under the same mentioned regions during uphill walking compared to level

walking. Moreover, the findings showed an excessive increase in several plantar parameters: peak pressure, force-time integral, and pressure-time integral registered under the whole foot, forefoot, and hallux regions while the older subjects performed downhill walking tasks in contrast to that of walking on level surfaces. These measurements could be useful as a reference value for the clinical arena, particularly for physical injury diagnosis and treatment concerning these walking activities.

Additionally, the risk of falls experienced by older people can increase because of instability and body balance impairment that, in turn, may affect foot function during walking. Most foot complaints, including falls sustained by older adults, occur during gait. The evaluation of foot and gait pathologies can be implemented by assessing the measurements of plantar loading patterns for both scientific and clinical fields. Much research has focused on evaluating plantar pressure distribution considering data for the whole stance phase as one assessment. Few investigations have studied plantar loading patterns in each specific gait phase individually, particularly plantar pressure measurements in these phases during gait between older adults and adults. Therefore, this research study investigated the plantar pressure parameters measured during five loading phases of the gait cycle. These measurements provide an overall understanding of changes in plantar loading patterns with advancing age in the selected phases. The variation of plantar parameters, which occurred with increasing age, was observed via employing comparisons between older adults and adult subjects. This aim provided insights into common changes occurring with advancing age in pressure measurements distributed at fifteen plantar regions during the gait loading phase. During the gait trials, the subjects walked barefooted with floor-based pressure mat systems capturing the pressure parameters. The study provided further insights into whether there was a chance of developing plantar tissue damage related to each specific phase under investigation for older adults. Results demonstrated higher contact pressure and peak pressure for older adults, mainly through the mid-stance, push-down, and toe-off phases. These higher values were located underneath the forefoot region, especially at the metatarsal heads and the hallux areas. Therefore, these regions could be assessed as vulnerable throughout the entire plantar surface for people of older age.

The research also investigated the body weight of subjects' and the total time to complete the gait loading phase while analysing pressure parameters. These parameters were examined during the single-limb support phase when one lower limb has the full responsibility for carrying the body weight. The pressure distribution was measured and compared between the two cohorts participating in the study: older adults and adults. The results revealed higher pressure and peak pressure values under most of the selected foot regions for older adults than those measured for adult individuals. The results showed close similarities to those conducted for initial measured plantar pressure parameters.

This investigation also involved innovative techniques for measuring the correlation between 3D gait phase images and corresponding plantar pressure images. Foot rotation and loading was examined by comparing human lower limb movement with corresponding plantar pressure parameters. A low-cost photogrammetric technique was used to obtain high-accuracy measurements of anthropometric landmarks positioned on human lower limbs during the heel-strike, mid-stance, and toe-off phases. As another form of measurement, the Tekscan Matscan system was adopted to evaluate plantar pressure data, particularly the centre of pressure trajectories during the heel-strike, mid-stance, and toe-off phases. The correlation technique was implemented by integrating the two sets of captured data. The integrated data was significant in distinguishing the difference in gait characteristics between cohorts. These comparisons permitted an enhanced evaluation of the gait based on barefoot walking between the two participating groups: older adults and adults. The research results enhance insights into the reasons beyond foot complaints associated with individual gait characteristics, which enable solutions for coping with these problems, thereby minimising risks facing older people during gait.

CERTIFICATION OF THESIS

This Thesis is the work of Mrs Nibras Abbas 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: *Professor Peter Milburn (Griffith University, Gold Coast)*

Student's and Supervisors' signatures of endorsement are held at the University of Southern Queensland.

PUBLICATIONS

Papers published from this thesis

Abbas, N.S. and Chong, A.K. 2018. 3D video imagery of the foot and plantar pressure to examine foot rotation and loading for older adults, pp. 349-353, IEEE. (Published in 2018 8th IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)).

Abbas, N.S. and Chong, A.K. 2019. Un-normalised and Normalised Plantar Pressure Distribution Comparison between Older Adults and Adults while Single limb Support Interval, pp. 213-218, IEEE. (Published in 2019 9th IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)).

Abbas, N.S. and Chong, A.K., 2021, April. Loaded Gait Phase of Normalised Comparison between Older Adults Aged 65-80 Years and Adults Aged 25-45 Years. In 2021 IEEE 11th IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE) (pp. 313-318). IEEE.

Papers prepared for submission from this thesis

Abbas, N.S. and Chong, A.K. 2021. Loaded Gait Phase of Un-normalised and Normalised Comparison between Older Adults Aged 65-80 Years and Adults Aged 25-45 Years. (Prepared for submission).

Abbas, N.S. and Chong, A.K. 2021. Loaded Gait Phase Comparison for Older Adults Aged 65-80 Years between Level and Inclined Surfaces. (Prepared for submission).

Abbas, N.S. and Chong, A.K. 2021. Investigation of Pedobarographic Image Characteristics for Comparison between Older Adults and Adults during Heel-strike, Foot-flat, Mid-stance, Push-down, and Toe-off Phases of the Gait. (Prepared for submission).

Other associated publications

Abbas, N.S., Chong, A., Al-Kharaz, A.A. and Al-Hadeethi, H. 2020. Relationships between Foot Dimensions and Plantar Pressure Distributed in Older People, pp. 198-202, IEEE. (Published in 2020 10th IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)).

Al-Kharaz, A.A., Chong, A. and Abbas, N.S., 2019, December. Pedobarography assessment of hindfoot gender in Middle Eastern adults during gait. In 2019 13th International Conference on Signal Processing and Communication Systems (ICSPCS) (pp. 1-3). IEEE. (Published in: 2019 13th International Conference on Signal Processing and Communication Systems (ICSPCS)).

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious, the Ever Merciful

First and foremost, I would like to thank God for his never-ending grace, mercy, and provision during what ended up being the toughest times of my life. Without his blessings, this achievement would not have been possible.

I gratefully acknowledge the financial support of the Iraqi Government provided to pursue this doctoral study. In addition, this research has been supported by an Australian Government Research Training Program Scholarship. I would like to express my deepest gratitude to my principal supervisor, Dr Albert Chong for giving me this invaluable opportunity, as well as his excellent guidance and encouragement throughout my PhD study. Without his valuable support, it would not have been possible to conduct this research study successfully. I greatly appreciate the collaboration of Professor Peter Milburn for his encouragement and guidance in the completion of this study.

I would like to sincerely thank Dr Barbara Harmes for her excellent English language support for my thesis. I would also like to thank Dr Angela Murphy for reminding me to take a deep breath during thesis submission time. Finally, my sincere appreciation goes to my parents, husband, sons, brother and sisters for supporting me spiritually during the entire doctoral study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SD	Standard deviation
CA	Contact area
CP	Contact pressure
F	Force
PP	Peak pressure
FTI	Force-time integral
PTI	Pressure-time integral
ICC	Intraclass correlation coefficients
IMD	In-shoe multisensory pressure sensors
COP	Centre of pressure
TF	Total foot
MH	Medial heel
LH	Lateral heel
MM	Mid-foot
MMF	Medial mid-foot
LMF	Lateral mid-foot
MFF	Medial forefoot
LFF	Lateral forefoot
M1	First metatarsal head
M2	Second metatarsal head
M3	Third metatarsal head
M4	Fourth metatarsal head
M5	Fifth metatarsal head

T1	Toe 1
T2	Toe 2
T3	Toe 3
T4	Toe 4
T5	Toe 5
T45	Toe 4, and 5
HS	Heel-strike
FF	Foot-flat
MS	Mid-stance
PD	Push-down
TO	Toe-off
PD	Principal distance
LED	Light emitting diode
MFA	Medial foot axis

CHAPTER ONE

INTRODUCTION

1.1 General overview

Human gait characteristics determine the way people walk. Several biometric features, for example, age, gender and identity are identifiable from human walking patterns. The unique pattern of an individual's gait through the movement of their upper and lower limbs has encouraged numerous recent computer vision publications (Bora et al., 2015; Wang et al., 2004). From the moment one foot has heel ground contact until the heel strike of the same foot in preparation for the next step is defined as the human gait cycle (Perttunen, 2002).

With advancing age, the increasing number of foot complaints can significantly limit human mobility because the foot represents the vital animated part, the connection between the human body and the ground (Keijsers et al., 2013; Menz, 2015; 2016; Rodgers, 1995). Foot complaints, sustained with increasing age, are associated with an increased risk of falling, limiting body balance during gait, and developing several gait disorders (Abouaesha et al., 2001; Armstrong et al., 1998; Keijsers et al., 2013). A clear understanding of the dynamic behaviour of normal foot function would, therefore inform valuable insights into age-related gait variability (Callisaya et al., 2010).

Research study and clinical practice have leveraged measurement of the parameters of plantar pressure distribution to compare gait patterns of various clinical cohorts and evaluate the impacts of footwear, orthotic devices, and surgical intervention (Orlin et al., 2000; Taylor et al., 2004). Measuring dynamic loading patterns can identify anatomical foot deformities (Hessert et al., 2005; Rodgers, 1995; Tanaka et al., 1996), which may contribute to an limitation of body balance and a deterioration in functional abilities for older adults (Menz et al., 2005). Providing comparisons between older adults and adults can permit a full visualisation of the main differences in plantar pressure distribution that commonly occur for older people during the whole stance phase of the gait cycle. This visualisation could be intrinsic to foot assessment in clinical scopes to identify treatment strategies that prevent a broad range of foot complaints and deformities sustained by older people.

The body balance task during standing for older people can be sufficiently maintained by the activities of the human ankle muscles (Huxham et al., 2001; Nashner, 2014; Winter, 1995; Woollacott et al., 1997). However, during walking, the activity of the human ankle muscles alone is insufficient to provide the control necessary for body balance, especially with sudden events such as trips and slips (Winter, 1995; Woollacott and Pei-Fang, 1997). A higher incidence of such events can increase the risk of falling (Woollacott and Pei-Fang, 1997), particularly for older people with foot deformities (Mickle et al., 2009). In addition, maintaining body balance during walking can be influenced by the characteristics of the gait task being performed (Carry et al., 1998; Huxham et al., 2001). Therefore, the challenge of maintaining balance control is enhanced with increasing age when walking on uneven surfaces rather than walking on level surfaces. Assessment of the distribution of plantar loading patterns in older adults can help provide a review of gait characteristics during different walking tasks, including walking on level surfaces and walking uphill or downhill. This information could be useful in clinical fields as a reference value for the diagnosis of foot and gait pathologies and the treatment of foot injuries for older people.

Implementing human body measurements and mapping requires multi-camera imaging systems to be involved due to the complicated human body shape, especially in the craniofacial area, the hands and the feet (Chong, 2011; Chong et al., 2006; Martedi et al., 2009). Photogrammetric systems can extract the geometric properties of an object or body part and 3D coordinates of required points on its surface. Photogrammetry procedures include capturing digital photographs using a multi-video camera and processing them with a photogrammetric software package to create a 3D model. The capture of high-accuracy 3D spatial data using photogrammetry is fundamental for several applications within medicine and physiotherapy, exercise science, forensic study and the manufacture of shoes (Fryer et al., 2007). The current research investigates a new method for thoroughly analysing gait patterns by combining 3D geometrical lower limb movement data with plantar pressure data. A multi-video camera system was used to capture a 3D model of the human lower limb and foot during locomotion, combined with a plantar pressure sensing system to capture plantar pressure parameters. The photogrammetric-plantar pressure technique proposed can discriminate the gait characteristics of older adults and adults, thereby enhancing several applications, particularly in physiotherapy and the manufacture of shoes.

An adult (according to the Cambridge Dictionary) is a person over 18 years old who has grown to full size and strength. The research will consider the ages of 25 – 45 and the ages of 65 – 80 for adults and older adults, respectively. The research findings enhance the understanding of the gait cycles' stance phase, including the body balance between the cohorts during heel-strike, mid-stance and toe-off. The chapter begins with the research gaps and the research aim, followed by the research objectives and research questions. A discussion of the theoretical and practical significance of the study follows, concluding with a brief listing of the thesis outline.

1.2 Research gaps

According to the literature review highlighted in chapter two, the research gaps investigated include:

1. The plantar loading patterns as a set of standard values for a group of healthy older adults, particularly the comparisons of their gait parameter measurements with the corresponding findings from adult individuals are not provided in the literature. This investigation involves measuring the plantar pressure distribution during normal walking at self-selected speeds. F-scan pressure sensor insoles as a measurement system were used to capture the pressure parameters during the whole stance phase of the gait cycle. This gap is linked to objective 1, 2, 4, and 5.
2. Previous research has not investigated the plantar pressure patterns of healthy older adult individuals to study the variations in gait patterns between walking on level surfaces, and with uphill and downhill walking while wearing pressure sensor insoles. This gap is linked to objective 3.
3. Published studies have not explored the capture of a dynamic 3D model of the human lower limb during gait using video imaging (the photogrammetric techniques) with high accuracy. Also, the precise correlation between the dynamic change in the 3D model of the human lower limb, and the

measurements of plantar pressure patterns while in the loading phase of gait, particularly for older adults and adults, has not been reported previously. This gap is linked to objective 6.

1.3 Research aim

This study investigates the statistical difference in gait loading patterns between older adults and adults during the whole stance phase of the gait cycle. This is addressed through objective 1 and 2 and also through objective 4 and 5.

This investigation also explores the statistical difference in gait loading patterns between walking on level surfaces and uphill and downhill walking steps activities. The particular focus will be a group of older individuals during the whole stance phase of the gait cycle. This is addressed through objective 3.

The research outcomes included developing innovative procedures to capture high accuracy dynamic 3D anthropometric measurements of the human lower limb using close-range photogrammetric techniques. Correlations with the corresponding plantar pressure data during the loading phase of gait were investigated. The developed techniques were adopted to determine the difference in gait characteristics between the two participating cohorts: older adults and adults during the heel-strike, mid-stance, and toe-off phases. This is addressed through objective 6.

1.4 Research objectives

Objective 1: Examine the variations of dynamic plantar pressure between older adults and adults (Chapter 3).

The gait patterns of normal walking for the older adults' group were compared to the adult subjects' group in five anatomically defined plantar regions to thoroughly understand the causes of developing foot problems and body balance shortages during the whole stance phase of the gait cycle.

Objective 2: Evaluate plantar pressure parameters based on the average weight for both participating groups: older adults and adults (Chapter 3).

Average weight was included as a factor during the analysis of gait parameters to observe the impact on plantar pressure distribution comparisons compared to those conducted for initial measured plantar pressure parameters between older adults and adults. Gait trials were performed as subjects walked at self-selected speeds using an insole pressure sensor system.

Objective 3: Evaluate the loaded gait phase comparison for older adults between level and inclined surfaces (Chapter 4).

The measurement of plantar pressure parameters distributed beneath the human foot plantar, wearing pressure sensor insoles, enables the generation of a reference value as a comprehensive set to examine the distribution of body weight. Various gait conditions were examined, for a number of older adult subjects, including walking on level surfaces, uphill and downhill walking steps. The influence of these tasks on body balance and stability were investigated with a focus on self-selected speeds underneath five anatomically defined foot plantar regions.

Objective 4: Evaluate the plantar pressure patterns for older adults and adults during five gait phases included in the stance phase of the gait cycle (Chapter 5).

Plantar pressure measurements distributed under fifteen anatomically defined foot regions, covering the whole plantar surface, will be analysed for both participating groups: older adults and adults. The plantar pressure distribution will be studied for the five phases included in the stance phase of the gait cycle, whereby the foot is in contact with the ground. This information enhances understanding of the underlying causes of impaired the balance during gait with advancing age and determines whether foot complaints and instability of walking are associated with specific phases of the gait cycle.

Objective 5: Investigate whether taking into account the pressure parameters normalised to subjects’ body weight, and to the time required to finish the stance phase can alter the pressure and peak pressure comparisons compared to the un-normalised pressure parameters comprisons between the two cohorts: older adults and adults. The pressure measurements were analysed during single limb support intervals (Chapter 5).

Objective 6: Develop a new technique of 3D gait phase image and plantar pressure data to compare the gait characteristics between the two participating groups: older adults and adults (Chapter 6).

This investigation involved innovative techniques to correlate human 3D gait phase images and the corresponding plantar pressure images. Firstly, 3D models of the human lower limb were obtained using photogrammetric techniques, with plantar pressure data acquired through floor-based pressure mat systems. Secondly, the correlated data was adopted to identify discrepancies in the gait characteristics between older adults and adults while performing typical barefoot walking. Foot rotation and loading was examined based on integrating the human lower limb movement with its corresponding plantar pressure data.

1.5 Research questions

The research questions for this study are as follows:

1. Are there statistically significant variations in plantar pressure distribution measurements during horizontal walking at self-selected speeds wearing insole pressure sensors under five anatomically defined foot regions between a group of older adults and adults during the whole stance phase of the gait cycle? This question has been addressed in Chapter 3.
2. Are there statistically significant variations in plantar pressure distribution measurements during horizontal walking at self-selected speeds when accounting for the weight factor in conjunction with analysing plantar parameters between a group of older adults and adults? The investigation encompassed the whole stance phase of the gait cycle. This question has been discussed in Chapter 3.
3. Are variations in plantar loading patterns affecting body balance and leading to foot complaints with increasing human age? This question has been addressed through Chapter 3.
4. Are there any significant differences in plantar loading patterns between walking on level surfaces and uphill walking activities, as performed by a group of healthy older adults? This question has been discussed in Chapter 4.

5. Are there any significant differences in plantar loading patterns between walking on level surfaces and downhill walking activities performed by a group of healthy older adults? This question has been discussed in Chapter 4.
6. Are there any noticeable differences in the centre of pressure trajectories with advancing age that can affect the body balance and lead to foot complaints? This question has been answered in Chapter 4.
7. Are there any noticeable differences in plantar loading distributed under fifteen anatomical plantar regions during gait when the subjects are barefooted at heel-strike, foot-flat, mid-stance, push-down, and toe-off phases? These phases are included in the stance phase of the gait cycle. Measurements were compared between the two participating cohorts: older adults and adult individuals. This question has been addressed through Chapter 5.
8. What is the protocol, to be used during the data collection process, which can achieve the required reliability with limited numbers of gait trials since the main subjects of the present study are older adults? This question has been discussed in Chapter 5.
9. What are the most vulnerable plantar regions that are more likely to be affected during the loading phase of gait with increasing age? This question has been answered in Chapter 5.
10. In the context of analysing plantar pressure measurements based on subject's weight and the time taken to complete the stance phase of the gait cycle, are the weight-normalised or time-normalised plantar pressure distribution measurements reflecting the same outcomes as un-normalised data? Comparisons were undertaken between subjects from both participating groups: older adults and adults. Measurements were analysed during single limb support intervals. Participants performed barefoot gait trials using floor-based pressure mat systems. This question has been addressed through Chapter 5.
11. Are close-range photogrammetric systems suitable for capturing high accuracy 3D measurements of anthropometric landmarks located on the human lower limb during gait? This question has been discussed in Chapter 6.
12. Can the technique developed to correlate 3D lower limb and foot measurements with the corresponding plantar pressure data enhance the visualisation of the difference in gait characteristics between both groups

participating in the study: older adults and adults? Participants performed the gait trials while on barefoot walking conditions at self-selected speeds. The lower limb movement was captured using photogrammetric techniques. The plantar pressure measurements were captured using floor-based pressure mat systems while in the loading phase of gait. This question has been answered in Chapter 6.

1.6 Significance of the study

Completing this research may bring several substantial benefits. These are:

1. Providing plantar pressure patterns analysed during the entire stance phase of the gait cycle for the two selected groups: older adults and adults, is useful for human gait study. This analysis will enhance the visualisation of plantar pressure distribution of the whole plantar surface, which improves understanding of the plantar pressure pattern variations due to the ageing factor.
2. The plantar pressure measurements distributed under a number of plantar regions for healthy older adults during the whole stance phase of the gait cycle, wearing in-shoe sensors can be useful in various fields. The captured measurements provide standard values of the plantar parameters to support clinical scopes for comparing different gait pathologies encountered by older people. For instance, the generated standard values inform the assessment of various foot complaints that predominantly occur during gait.
3. New understanding of plantar pressure variations due to the ageing factor provide new insights into the causes of impairments to the maintenance of body balance necessary for older people during walking. This information enables footwear design to support the needs of older adults or informs clinical interventions designed to avoid the development of foot complaints.
4. Providing an evaluation of plantar pressure measurements for older adults during various walking tasks can enhance the visualisation of the pressure measures distributed beneath the whole plantar surface related to each selected walking condition. These conditions include walking on level surfaces, and uphill and downhill walking steps. This information can contribute to a

comprehensive understanding of the body balance problems associated with these gait tasks.

5. The distribution of plantar pressure measurements undertaken for older adults in the present study can generate a reference value for clinical diagnosis of foot pathologies and injuries and inform treatment strategies for different walking difficulties among older cohorts.
6. Better understanding the variations in plantar pressure patterns for different walking tasks can assist in optimising customised footwear design to suit older people's needs and minimise the risk of falling while walking on uneven surfaces.
7. Providing improved techniques in the capture and analysis of the 3D measurements of anthropometric landmarks placed on the human lower limb during gait uses advanced low-cost, high-accuracy photogrammetric image processing techniques.
8. The development of new techniques in the precision correlation of the 3D lower limb and foot physical model and pressure recording are enabled.
9. New knowledge can be advanced by combining the 3D lower limb and foot physical model and the plantar pressure data.
10. Enhanced insight into the variation of gait characteristics between older adults and adults will inform new knowledge in the understanding of the gait characteristics between the cohorts during heel-strike, mid-stance and toe-off.

1.7 Thesis outline

The outline of the research is as follows:

Chapter 2: Literature Review.

The chapter provides an overview of relevant literature to provide the research objectives.

Chapter 3: Loaded Gait Phase of Un-normalised and Normalised Comparison between Older Adults Aged 65-80 Years and Adults Aged 25-45 Years.

The chapter details the examination of the variations in dynamic plantar pressure patterns between older adults and adults. The gait patterns of normal walking for the older adults' group are compared to the adult subjects' group under five anatomically defined foot regions, wearing pressure sensor insoles. These gait patterns inform the causes of low body balance and foot complaints for older adults during the entire stance phase of the gait cycle. The chapter also presents the evaluation of plantar loading patterns based on the average weight for each group; investigating whether the computed data has changed the plantar pressure distribution comparison undertaken for the initial measured data between the two selected cohorts during gait.

Chapter 4: Loaded Gait Phase Comparison for Older Adults Aged 65-80 Years between Level and Inclined Surfaces.

The chapter details the measures of plantar pressure parameters distributed under the human foot wearing in-shoe pressure sensor insoles. The captured measurements can enable a thoroughly examination of the distribution of the body weight for a number of older adult individuals during various walking conditions. These conditions include walking on level surfaces, and uphill and downhill walking steps. The study investigates the influence of these tasks on the body balance and stability for older adults through an individual examination of plantar parameters and the centre of pressure trajectories for a number of older adults.

Chapter 5: Plantar Pressure Characteristics Comparison during Heel-strike, Foot-flat, Mid-stance, Push-down and Toe-off Phases of Gait between Older Adults and Adults.

The chapter addresses the evaluation of the plantar pressure patterns for the two participating groups: older adults and adults. The pressure parameters are assessed during five gait phases of the human gait cycle, whereby the foot is in contact with the ground. The plantar pressure distribution is measured under fifteen anatomically defined plantar regions, covering the entire plantar surface. The evaluation of the gait parameters focuses on increasing age and assists in thoroughly studying the underlying causes of foot complaints during walking, in particular to find out whether foot problems and the loss in body balance sustained by those people are associated with specific phases. The chapter also presents the evaluation of whether taking into consideration the parameters analysed in accordance to subjects' body weight, and to the time required to complete the stance phase can change the pressure and peak pressure comparisons between the two cohorts, compared to comparisons undertaken to initial measured data during single limb support intervals.

Chapter 6: Advanced Techniques of 3D Gait Phase Image and Plantar Pressure Comparison between Older Adults and Adults.

This chapter investigates innovative techniques to carry out the correlation between 3D gait phase images and the corresponding plantar pressure images to examine foot rotation and loading. The 3D measurements of the human lower limb and foot during gait are obtained using an image-based measurement technique suitable for dynamic lower limb anthropometric data collection based on the concepts of photogrammetry. In this way, a set of plantar pressure data is acquired via floor-based pressure mat systems. The correlation of analysed gait measurements and plantar pressure data is based on the integration of both measurements. The created data are adopted to examine the discrepancies in gait characteristics between older adults and adults.

Chapter 7: Conclusion and Future Research Recommendations.

The thesis concludes with summarising the research outcomes along with several recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In the previous chapter, a number of fundamental research points were outlined. This chapter provides a detailed overview of the relevant literature for the provision of better understanding of the research objectives. Firstly, the chapter begins with a general overview of the human gait cycle, followed by a section to present the gait characteristics associated with specific pathologies and age-related changes. Studying plantar pressure patterns is of particular interest for both research and clinical settings due to the valuable information provided to evaluate and assess a number of significant changes related to human lower extremity complaints, disorders, and foot deformities. Hence, the following sections provide a general overview of plantar pressure measurements, plantar pressure patterns in relation to older people, and an overview of the systems existed to evaluate plantar pressure distribution, in particular the devices that have been adopted in the present study. Next, the chapter introduces the suitability of plantar pressure systems for the evaluation of foot problems relating to sport activities. Subsequently, the chapter discusses how both footwear and walking speed are associated with altered plantar loading patterns. Then, the chapter presents the loaded gait patterns during walking on uneven surfaces and their association with age-related human foot changes. Finally, the chapter ends with sections demonstrating the 3D modelling studies, 3D spatial measurements obtained by photogrammetric techniques in the literature, and the integration between 3D lower limb and foot data with the corresponding plantar pressure data. The conclusion highlights the systems that are most accurate and efficient for obtaining precise 3D spatial measurements of the human lower extremity and plantar pressure distribution measurements.

The relation between the categories of the cited works in this chapter with the tasks included in this thesis is illustrated in the following points:

Human gait analysis

1. Plantar load distribution.

- Plantar load distribution for older people: this has been discussed in chapter 3, 4, 5, and 6.
- Plantar pressure measurement systems.
    - Platform pressure mat systems: this system has been used for data analysis in chapter 5, and 6.
    - In-shoe pressure pad systems: this system has been utilised for data analysis for subjects selected in chapter 3, and 4.
- Footwear association with altered plantar pressure distributions: subjects have been tested while wearing shoes in chapter 3 and 4; however, the selected subjects were on barefoot conditions for the task required in chapter 5, and 6 as the system adopted for data analysis is floor-based pressure mat.
- Walking speed association with altered plantar pressure patterns: walking speed and its association with plantar pressure measurements has been discussed through chapters 3 to 6.
- Loaded gait phase for uneven walking surfaces and its association with age-related changes: this has been linked to chapter 4.

2. 3D modelling and lower limb studies
    - Photogrammetric techniques
        - Video camera system: Close range photogrammetry as a 3D spatial measurement method has been used in this doctoral research for capturing human lower limb movements in chapter 6.
        - Camera and projector system
        - Time-of-Flight camera system

2.2 Human gait cycle

Human gait defines the locomotion of human lower limbs and feet, represented by a repetitious sequence of lower limb motions, resulting in moving the human body forward while preserving stance stability (Burnfield, 2010; Perry et al., 1993; Perry et al., 1992). The period from one foot heel ground contact until the next heel contact by the ipsilateral foot is what the research defines the gait cycle (Perttunen, 2002). Each gait cycle includes two main phases: stance and swing. The stance phase indicates the entire period whereby the foot is in contact with the ground (from initial contact by heel striking the ground to toe-off when the toes area pushes off the ground for forward progression).

The period from the toe-off phase until the next heel-strike by the ipsilateral foot, during which the foot is no more in contact with the ground, defines the swing phase of the gait cycle (Burnfield, 2010; Perry and Burnfield, 1993; Perry and Davids, 1992). Based on previous research, the stance phase period represents approximately 62% while the remaining period of the whole gait cycle forms the swing phase, which is approximately 38%. These percentages can vary according to the human rate of walking (Burnfield, 2010; Perry and Burnfield, 1993; Perry and Davids, 1992; Perttunen, 2002).

The stance phase includes three intervals: two double limb support and one single limb support. The two double stance intervals, involving bilateral human foot contact with the ground, occur with the commencement and termination durations of the stance phase of the gait cycle. The single limb support interval forms the middle period during the stance phase, which is characterised by one foot making contact with the ground, Figure 2.1 (Burnfield, 2010; Perry and Burnfield, 1993; Perry and Davids, 1992; Perttunen, 2002; Vaughan et al., 1999).

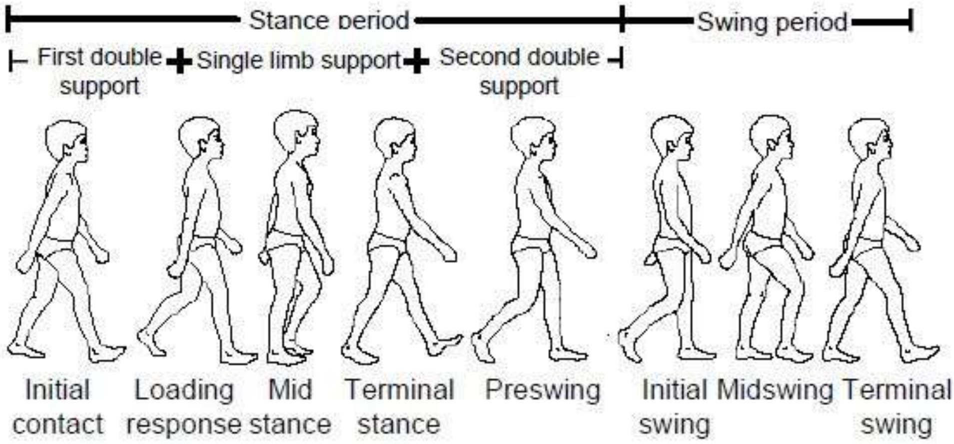

Figure 2.1: The gait cycle for an eight year old boy (Perttunen, 2002).

The first double limb support interval initiates the gait cycle by the heel-strike phase. The moment of foot contact with the floor is the most readily accessible action; therefore, it has been selected to represent the onset of the gait cycle. However, the term initial contact is usually used to describe the onset of the gait cycle because not all patients are able to initiate floor contact by their heel area (Burnfield, 2010). The initial contact phase starts the stance phase with a heel rocker for which the ankle is dorsiflexed, and the knee is extended. This phase is the one with more challenging task as it demonstrates the lower limb’s ability to transfer the body weight on that limb, which finishes the swing phase with unsteady alignment. As a result, the extremity has to resume its capability to maintain limb stability and preserve the progression of the body (Burnfield, 2010).

The second phase included in the initial double limb support interval is the loading response. This phase follows the initial contact phase and terminates when the other extremity is lifted from the floor, ready for the swing phase. Three objectives must be achieved during the foot-flat phase: 1) shock absorption; 2) weight-bearing stability; and 3) preservation of progression. On the loading response phase the limb undergoes changes as the body weight is transferred to that specific limb. In addition, the heel area’s touch with the ground continues for the entire period of this phase. While each double limb support interval forms approximately 12%, the single limb support interval forms about 38% of the whole gait cycle (Burnfield, 2010; Perry and Burnfield, 1993; Perry and Davids, 1992).

The first half included in the single limb support interval denotes the mid-stance phase, which occurs approximately from 12% to 31% of the gait cycle. The mid-stance phase commences when the contralateral extremity is lifted from the ground and continues until the body is vertically aligned over the portion of the forefoot belong to the same extremity. The mid-stance phase included in the single limb support interval is considered to be a period with functional significance for the limb because this extremity has to be responsible for supporting the weight of the human body. The duration of this phase can be used as an index of support capability of the limb. Hence, the single limb support interval can have clinically significant importance in the study of the human gait cycle related to pathological cases (Burnfield, 2010; Perry and Davids, 1992).

Furthermore, the terminal stance phase is the second and last period included in the single limb support interval. The phase is characterised by the moment of heel rise from the ground, and terminates when the contralateral extremity contacts the ground with a heel rocker. This moment starts the push-down phase when a human body weight progresses to the head of the forefoot area; hence, the human body advances the supporting foot as it progresses. The pre-swing represents the final phase of the stance included in the second double limb support interval. This phase begins with initial contact by the contralateral extremity and continues with ipsilateral toe-off. During this phase, an abrupt transfer of the human body weight to the opposite limb takes place, resulting in rapid unloading of the ipsilateral limb. This prepares the limb for the swing phase, and also contributes to accelerating the body progression with a propulsive forward movement (Burnfield, 2010; Perry and Burnfield, 1993; Perry and Davids, 1992).

By studying the foot motion from the initial contact and loading response through the mid-stance to the propulsive phases (push-down and toe-off), the provision of information can be central to understanding the characteristics of the human gait cycle.

2.3 Gait characteristics associated with pathologies and age-related changes

Despite the adaptations in walking made by older adults as a way to create more stable gait patterns, their forward progression can be affected, with less effectiveness than is desired. This can lead to balance deficits (Cromwell et al., 2004). Balance deficiencies are common in older adults. Age-related balance disorders are associated with increased risk of falling (Sturnieks et al., 2008).

Previous studies have indicated that approximately 30% of older people sustain one or more falls each year (Blake et al., 1988; Campbell et al., 1981; Day, 2003; Lamoth et al., 2011; Lizama et al., 2015). A number of studies have pointed out that about 30% of the above percentage of falls take place during gait, particularly with specific events such as slips and trips (Bhatt et al., 2011; Gabell et al., 1985; Lord et al., 1993; Tinetti et al., 1988; Topper et al., 1993). It is believed that balance control during walking for human systems is a challenging task because it contains two single limb support intervals, which form about 75% of the entire gait cycle. It is probable that during single limb support intervals, a mediolateral instability might occur (Shimba, 1984; Sutherland, 1994; Woollacott et al., 1997).

Prior studies have shown an association between falls in older people and the resulting serious injuries and the beginning of a decline in their independence (Sturnieks et al., 2008). Falls have been shown to be one of the main causes of death for people aged sixty-five and over (Berg et al., 1997; Hamacher et al., 2011; Kang et al., 2008a; Menz et al., 2018; Rubenstein, 2006).

Gait variations are common with advancing age, characterised by: 1) slower walking speed; 2) shorter step length; 3) wider step width; and 4) more time spent in double limb support intervals (Elble et al., 1991; Martin et al., 2013; Sturnieks et al., 2008). A number of studies have investigated the gait characteristics for older adults, which emphasised a decline in the performance of spatio-temporal gait parameters with advancing age (Beauchet et al., 2017). In a study of thirty older subjects aged 60 – 80 years, and thirty young subjects aged 20 – 40 years, a video motion system was used to analyse the difference in gait characteristics between the two groups. The results showed significant variations in the gait patterns for the two participating groups, revealing a shorter stride length and less extension in knee movements for older adults compared to younger subjects (Ostrosky et al., 1994). Figure 2.2 displays the spatio-temporal gait parameters measured in a study conducted by Janeh et al. (2017).

In addition, in a sample of a number of older people aged 60 – 86 years, a study of aging and its influence on changing the gait spatial and temporal parameters was conducted by Callisaya et al. (2010). The study revealed a greater variability in step time, step length, and step width parameters with a probable increase in risk of falling due to poor postural stability (Callisaya et al., 2011; Callisaya et al., 2010; Hausdorff et al., 1998; Maki, 1997).

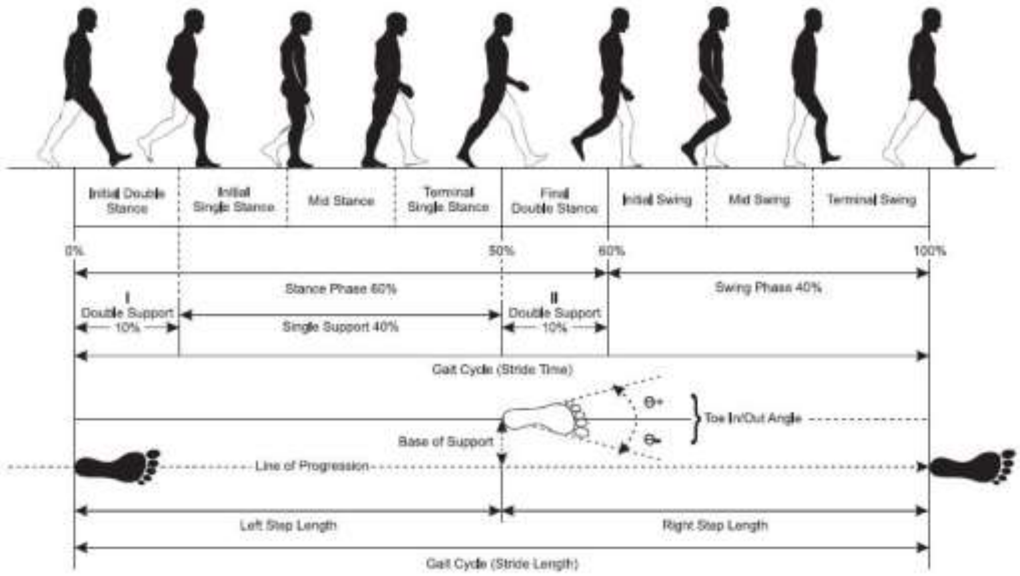

Figure 2.2: Spatio-temporal gait parameters (Janeh et al., 2017).

Several studies have emphasised that there is an association between aging and a greater variability in step length parameter measured for older adult groups (Grabiner et al., 2001; Kang et al., 2008b; Woledge et al., 2005). Other studies highlighted a greater variability in step width parameter in older people (Grabiner et al., 2001; Owings et al., 2004; Stolze, 2000; Woledge et al., 2005). Greater variability in step width parameter was found to be an indication of balance control impairment during gait (Gabell et al., 1984). For instance, older people tend to adapt their gait characteristics including step width and duration of double limb support intervals in order to compensate for the deficiencies in balance control (Gabell and Nayak, 1984).

It is possible that foot pains, complaints, disorders, and other pathological conditions can lead to variability in gait measures for people with these cases, particularly for people of advancing age. Other complications, often associated with advancing age are the cumulative impacts of obesity and chronic low back pain on gait patterns, which have been investigated by Cimolin et al. (2011). Obese participants with and without low back pain have been enrolled in the study to be assessed and compared with healthy participants. A gait pattern has been analysed for the cohorts showing that the stance duration increased while the step length decreased for obese participants with low back pain compared with other groups. Furthermore, it was evident that people with obesity and low back pain had low knee flexion and low dorsiflexion in stance and swing when compared with obese people. This demonstrated that obese people with low back pain are suffering from alteration of knee and ankle strategies while walking.

A comparison of gait parameters of diabetic patients with and without neuropathy and healthy individuals has been presented to aid in the understanding of the reason for increased fall risk of those patients (Allet et al., 2009). The participants' gait has been assessed using a variety of walking surfaces. Spatial and temporal gait parameters and stride to stride alteration were measured. A significant difference was observed between diabetic patients and healthy people. From the results of that study, it was suggested that the fall risk increases drastically accompanied by a decrease in gait capacity with the development of diabetic disease.

Increasing the plantar pressure is considered the main reason for the emergence of foot ulcers. Amemiya et al. (2014) analysed the relationship between increased plantar pressure and gait features for diabetic patients. The F-scan system was used to measure plantar pressure distribution in four segments under the foot during stance phase while wireless motion sensors were used to measure gait features. It became evident that elevated plantar pressure in diabetic patients was due to the small roll and yaw motions of the body and the small yaw motion of the foot as well in the phase of mid-stance. It was concluded that increasing the motion of the foot during the mid-stance phase can help in preventing ulcerations in the foot of these patients. The study of gait differences in diabetic patients with peripheral neuropathy and aged-matched controls during long and short walking distance was explored (Najafi et al., 2013). The experiments were implemented during barefoot walking and with regular shoes. The spatiotemporal gait parameters were measured. During long walking distance, the difference in gait characteristics between the two groups was significant. The double support times in both shod and barefoot conditions were longer in diabetic patients with peripheral neuropathy while walking long distances. Furthermore, gait unsteadiness of this group was higher during long walking in barefoot conditions. From the study outcomes, it was apparent that gait steadiness was improved by 46% with the addition of footwear to this group.

Spatio-temporal gait parameters have been considered to be an indicator of the functional condition and the degree of secure ambulation among older people (Neumanm, 2002). A gait parameters difference study in elderly people, people with knee pain and those with walker dependent gait was presented by Lee et al. (2013b). A number of spatiotemporal gait characteristics were used for investigating the difference between groups and providing better understanding of the gait patterns for each group separately. Based on the results of the study, it was evident that gait parameters such as gait speed, stride length and time, and ankle flexion were significantly different between tested groups.

The toe-flexor muscles represent a vital function to control human foot movement and aid with the propulsive force during gait (Misu et al., 2014). In a study of community-dwelling older people the strength of the toe flexor was shown to be associated with spatio-temporal gait parameters. Gait analysis was undertaken on a 15-metre walkway for both usual and fast pace walking conditions. The findings showed a decrease in toe flexor strength. The decrease in the toe flexor strength had a significant association with the gait parameters under the fast pace conditions, revealing slower walking speed, lower duration of swing phase, and shorter stride length measured for older people. Hence, the toe flexor muscles strength has an important role in walking for community-dwelling older adults (Misu et al., 2014).

Research was conducted on a number of community-dwelling older people in the age range 65 – 90 years to study the spatio-temporal gait parameters for those people and associate these with a history of falls sustained by the subjects. The older people were arranged into strata, including the age, gender, disability, multi-morbidity, frailty, and use of multi-medications. The findings revealed that gait parameters measured under usual pace conditions, when participants were walking on an electronic measurement walkway, showed a significant difference in the stride length parameters between subjects who were fallers and those who were non-fallers. For instance, decreasing the stride length showed an independent association with falls in a group of men aged over 74 years. In relation to other stratification factors, the results showed that these factors were associated with different the spatio-temporal gait parameters assessed in that study (Thaler-Kall et al., 2015).

Gait variability and stride dynamics, as measurement factors of walking instability, have been used to identify the risk of prospective falls for older people with walking limitations and mobility defects (Hausdorff et al., 2001). A research study focussing on active older women aged from 55 – 90 years, to determine whether gait instability measurements can be used as an indicator for prospective falls risk, was conducted by Paterson et al. (2011). The results showed a reduction in inter-limb stride dynamics evaluated for active older women fallers. As a consequence, it has been established that inter-limb stride dynamics can be clinically used as an evaluation measurement for early detection of walking instability and corresponding risk of falls in the older community. In addition, fear of falling was shown to have an influence on changing the gait parameters for older people, with fearful people displaying slower walking speed, shorter stride length, longer stride width, and increased duration of the double limb support phase compared to more fearless older people (Chamberlin et al., 2005).

Spatial and temporal gait parameters have been adopted to study the influence of using different walking aids (Härdi et al., 2014; Mundt et al., 2019), and to investigate the effect of performing dual-tasks in community-dwelling older individuals (Guedes et al., 2014), while providing guidelines for clinicians willing to perform gait analysis implementation for older adults in clinical settings (Kressig et al., 2006). A number of other researchers have evaluated the spatio-temporal gait parameters for older people (Byun et al., 2016; Hartmann et al., 2009a; Hartmann et al., 2009b; Hollman et al., 2011; Vallabhajosula et al., 2019; Zijlstra, 2004).

Some studies have evaluated the gait variability between young and older adults for different research purposes such as: mental representation of the structure of the human gait (Stöckel et al., 2015), prediction of the severity of slip (Moyer et al., 2006), and assessing the reliability of spatial and temporal gait measurement systems (Menz et al., 2004). Other studies have evaluated the difference in gait parameters between young and older adults and how that is associated with gait stability. For most of these studies, there were significant variations between the two cohorts, revealing slower walking speed, shorter stride length, and larger step width relative to age-related human gait (Beauchet et al., 2009; Owings and Grabiner, 2004; Samson et al., 2001).

As was apparent from the above discussion, gait characteristics differences between adults and older adults can provide an insight into gait pattern changes with increases in human age. Hence, in the developed photogrammetric-plantar pressure technique adopted in the present study, the contact time of the entire stance phase of the gait cycle, which is mainly based on human walking speed and cadence, will be included for better understanding the variation in gait characteristics between the two participating groups: older adults and adults.

2.4 An overview of plantar load distribution

The distribution of plantar load has been widely used as an important tool in the research into human gait analysis (Perttunen, 2002; Ranu, 1986) because of the information provided about the physical interactions between the foot sole and supporting surface (Gerber, 1982; Orlin et al., 2000; Perttunen, 2002). The measurement of plantar pressure distributed under the human foot is of particular interest as it can provide valuable information related to the biomechanics of the human foot, foot stress and injuries (Castro et al., 2013; Hughes, 1993; Perttunen, 2002). The plantar distribution measurement is important for understanding the function of the human ankle and foot as both of these provide the support necessary for weight bearing during walking and other functional tasks (Orlin and McPoil, 2000; Soames, 1985). Plantar pressure distribution measurements have been extensively used for both the static evaluation of the human foot (Duckworth et al., 1985; Jonely et al., 2011; Kellis, 2001; Mao et al., 2006; Tuna et al., 2004), and for dynamic assessments (Fourchet et al., 2020; Hamada et al., 2019; Mochimaru et al., 2011; Sendur et al., 2019; Verdu-Roman et al., 2019; Wei et al., 2020).

With regard to the division of plantar surface into regions for plantar pressure measurements, a number of studies have evaluated the total foot with the four main regions: heel, mid-foot, forefoot, and toes (Demirbüken et al., 2019), other studies have divided the plantar surface into seven or eight regions (Hida et al., 2017; Menz et al., 2013; Zammit et al., 2008), with a number of studies dividing the plantar surface into ten or more, reaching to fifteen sub-regions in some studies (Aydos et al., 2012; Koller et al., 2014; Uzun, 2013; Xu et al., 2019), Figure 2.3. The plantar surface subdivision is more likely to be created depending on research requirements and whether it is necessary to focus on localised plantar regions, which are related to specific foot conditions. The current investigation adopts five anatomical foot regions, in chapters three and four, and identifies fifteen plantar regions clarified in chapter five, to study the gait characteristics variations between older adult and adult cohorts.

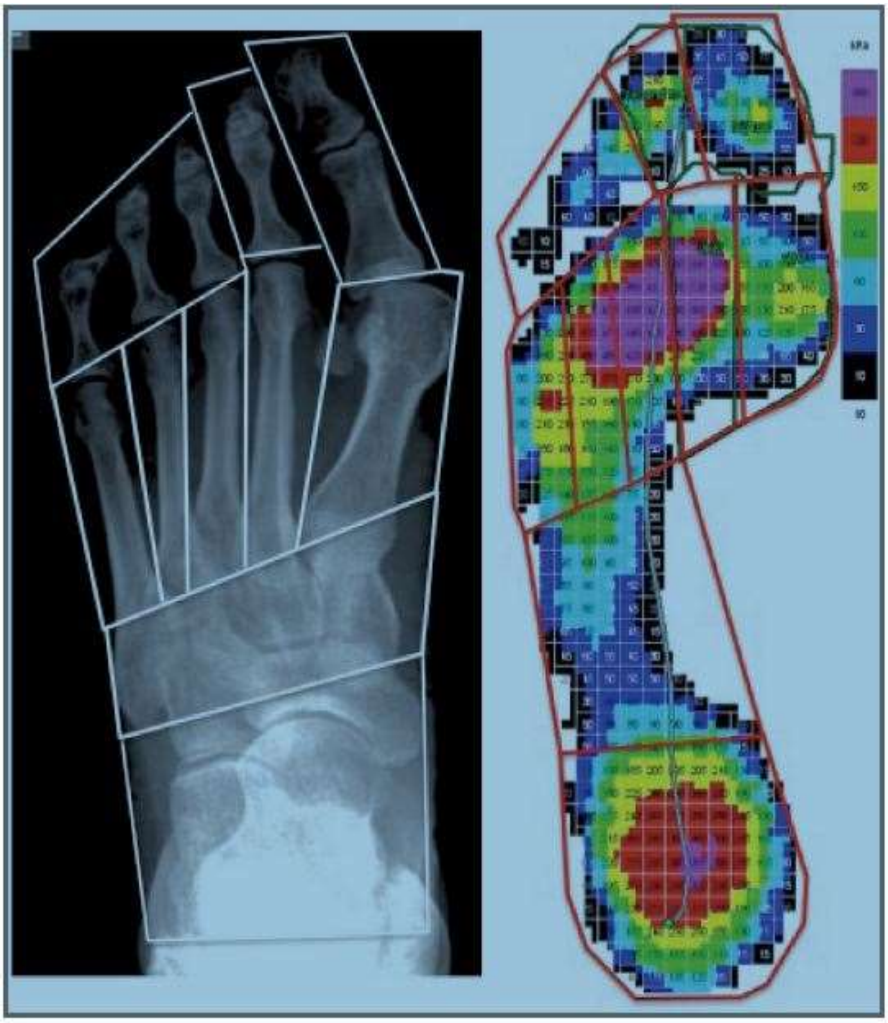

Figure 2.3: The plantar surface subdivided into ten regions displayed in the plantar image on the left, with the corresponding regions on the foot surface illustrated through radiographic image on the right side. The regions, including the total object, heel, mid-foot, forefoot, metatarsal heads 1, 2, 3, 4, and 5, hallux, toe 2, and toe (3 – 5), adopted from (Koller et al., 2014).

A number of studies have been conducted to evaluate the plantar pressure distribution in relation to different pathological cases (Fourchet et al., 2020; Martínez-Martí et al., 2019; Sendur et al., 2019; Verdu-Roman et al., 2019; Wei et al., 2020). The study of gait characteristics for obese children of different ages was conducted by Yan et al. (2014). A foot-scan plantar pressure system was used to measure the gait parameters. From the research results, it was apparent that the duration of heel-strike decreased for children 9-10 years old when compared to children 7-8 years old. It was also found that the duration of mid-stance increased for children 9-10 years old to children 7-8 years old. Furthermore, the peak plantar pressure increased under certain areas of the foot for 9-10 years old compared with children 7-8 years old. These changes might eventually lead to deterioration in the health of children in relation to their lower limb.

Barefoot plantar pressures measured under dynamic conditions have been utilised as a way to evaluate the foot for older adults and people with different pathologies because elevated plantar pressure seems to be a major risk factor in the development of tissue injuries, the leading cause of foot impairments encountered by those patients and older people during loading phases of gait (Burnfield et al., 2004; Bus et al., 2005a).

It is important to understand the dynamic behaviour of the normal functional foot to be able to compare it with the symptomatic foot of the patients (Rodgers, 1995; Rosenbaum et al., 1997). The anatomical foot deformities for those patients can be identified from the measurements of their plantar pressure patterns during locomotion (Hessert et al., 2005a; Rodgers, 1995). For instance, the appearance of ulceration and tissue injury risk can be caused by elevated plantar pressures during walking (Burnfield et al., 2004; Frykberg et al., 1998). In a sample of fourteen diabetic neuropathic patients, subjects have been requested to contact the pressure platform using various gait step protocols in order to obtain plantar pressure distribution based on the dynamic measurements for barefoot walking. A number of plantar pressure parameters have been analysed, including peak pressure, pressure-time integral, and contact time. Intraclass correlation coefficients were calculated for assessment of the reliability of the obtained results (Bus and de Lange, 2005a). Furthermore, a number of previous studies have been conducted for plantar pressure distribution measurements in association with diabetic patients (Barn et al., 2015; Chatwin et al., 2020; Gnanasundaram et al., 2020; Sutkowska et al., 2019; Waaijman et al., 2014; Xu et al., 2019).

Perttunen (2002) presented a number of studies to discuss the responses of foot loading in various loading cases, and to study how the foot loading pattern interacts with neuromusculoskeletal adaptation. These studies encompassed both normal and pathological walking. From the research findings, in both groups, the peak plantar pressure was found to be highest in three areas: under the heel, the forefoot, and the hallux, whereas the lowest magnitude of peak plantar pressures was located under the midfoot, which is illustrated in Figure 2.4.

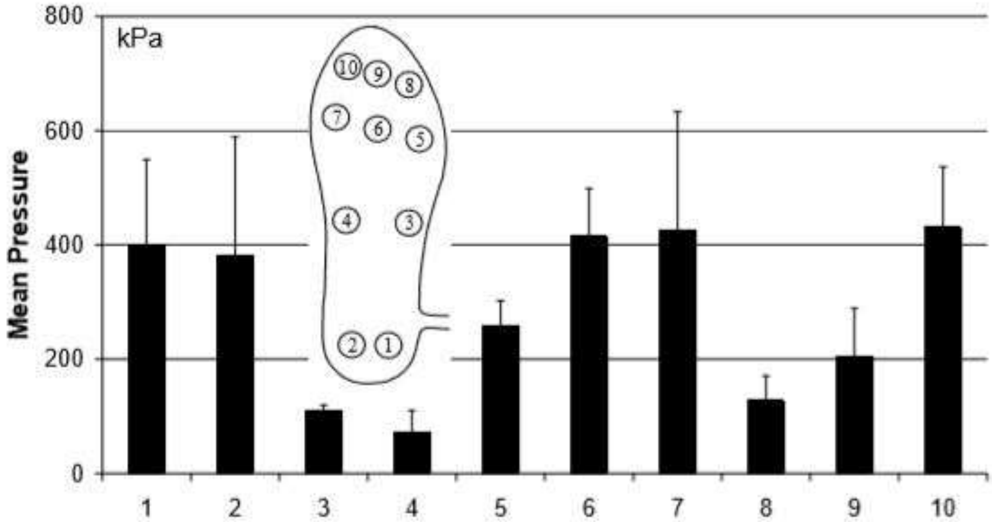

Figure 2.4: Peak pressure mean and SD values under a number of foot regions according to a number of plantar pressure distribution studies (Perttunen, 2002).

In addition, an accurate measurement of the plantar pressure parameters: peak plantar pressure and plantar pressure gradient, was considered to be significant for the most demanding gait analysis for both health and industrial applications. The development of foot pain for obese individuals has been studied (Butterworth et al., 2015). The relation between obesity and foot pain has been found to rely on higher values of peak plantar pressures during walking and increasing the loading of the foot, particularly beneath the forefoot and mid-foot areas thereby raising the stress applied to the foot plantar in relation to these regions. Other investigations have been undertaken to demonstrate the association of obesity with altered plantar pressure patterns across all ages (Butterworth et al., 2015; Fourchet et al., 2020; Mueller et al., 2016; Neri et al., 2017; Yan et al., 2020). These studies highlighted that plantar parameters for obese people showed different patterns compared to control groups of normal body weight.

The distinction in plantar pressure patterns between subjects of forefoot pain and others with normal foot conditions was investigated by Keijsers et al. (2013). The subject's plantar pressure image was analysed. A number of plantar pressure parameters were measured for data analysis: pressure, peak pressure, pressure-time integral, and the total contact time. From the research findings, it was apparent that the mean pressure and pressure-time integral values were higher under the second and third metatarsal heads for subjects without foot deformities accompanied by forefoot pain when compared with subjects of normal foot conditions. Furthermore, Stewart et al. (2016) conducted a study to identify the gait parameters and the distribution of the plantar pressure pattern during barefoot walking in order to make a comparison of findings from the participants with gout and participants with asymptomatic hyperuricemia with healthy individuals who have normal serum urate concentrations. Peak plantar pressures and pressure-time integrals were recorded using plantar pressure systems for all participants in order to distinguish between the gait characteristics of various medical conditions. For instance, the participants with gout proved to have a slower walking pace with an increase in the area of contact under the mid-foot region, and diminished values of peak pressure at the hallux area.

Ranu (1986) emphasised that beneficial information about foot structure and function could be achieved by studying the pressure distribution between the foot plantar and the ground. Several studies have investigated the plantar pressure distribution in association with the foot structure and function. A study by Scott et al. (2007) evaluated the differences in foot structure and function between young and older adults in relation to plantar forces and pressures. Foot characteristics such as range of motion and foot posture were measured for fifty young and fifty older adults. Furthermore, plantar pressure patterns were collected by a floor – mounted resistive mat sensor systems. The results revealed that there was a reduction in the range of motion, pronated foot, and a prevalence of toe deformities and hallux valgus with other changes in foot structure and function for older adults compared to young adults. The results also exhibited an alteration in plantar patterns under a number of plantar regions, suggesting that age-related changes in foot characteristics have been affected by the changes in foot posture and the hallux valgus conditions. These changes have contributed to an alteration in foot loading patterns for older adults. Moreover, plantar pressure parameters: peak pressure, maximum force, pressure-time integral, and force-time integral have been shown to be altered according to the type of foot (Hillstrom et al., 2013). In the next section, an overview of plantar pressure pattern and its association with age-related changes for both normal and pathological gait will be discussed in detail.

2.5 Plantar load distribution for older people

The vital animated human body part that connects the human body with the ground is the foot (Menz, 2016; Rodgers, 1995). Age-related changes in human gait have recently become a major focus for research because these changes could be the leading cause to falls sustained by older people. The scientific and clinical evaluation of foot and gait pathologies can be obtained by measuring the pressure parameters distributed beneath the human plantar surface (Hessert et al., 2005a; Rodgers, 1995). In general, the structure of the human foot changes with advancing age (Burnfield et al., 2004; Hessert et al., 2005a; Rodgers, 1995). In order to maintain independence and to diminish the falling risk for older people, it is vital for them to maintain the safety and efficiency of their walking ability (Callisaya et al., 2010; Mickle et al., 2011a).

It is well known that most foot-related problems, including falls, which are encountered by older adults occur during gait. It is important to have an extensive understanding of the dynamic charactersitics of normal functional foot to compare it with the symptomatic foot for patients in general and for other foot problems in relation to increasing human age (Rodgers, 1995).

Human gait can be utilised for assessing the quality of life, the health condition, and the physical function for older people (Cesari et al., 2005; Hollman et al., 2011). Because of age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during ambulation often result in injuries (Menant et al., 2008; Mickle et al., 2010a; Rubenstein, 2006). The risk of falls encountered by older adults may increase as a consequence of stability and balance impairment caused by any factor that may impair the foot function during normal gait (Mickle et al., 2010a). Foot pain is recognised as one foot-related factor that affects older adults in terms of gait, balance, and the changes in normal foot function (Menz et al., 2001). A number of recent studies have established that there is a clear association between foot pain and elevated plantar pressures that emerge for older people during gait. Forty subjects with a pes cavus foot type have been compared with thirty normal foot type subjects. It was found that there is a significant correlation between pressure-time integrals and foot pain, and the subjects suffering from foot pain had considerably higher values of pressure-time integrals for the entire foot than those who had no pain in their foot (Burns et al., 2005).

Foot pain disorders common among older adults can lead to the disruption of the biomechanical function, resulting in balance impairments and deprivation of independence (Menz, 2015; 2016; Oh-Park et al., 2019). A number of studies have assoociated the recurrence of falls with foot pain in older adults (Awale et al., 2017; Menz et al., 2006b; Patel et al., 2014; Stewart et al., 2012; Stubbs et al., 2014). In a study of community-dwelling older people in New South Wales, Australia, the association between plantar pressure pattern and foot pain with falls experienced by those people was investigated. The study concluded that elevated plantar pressure during walking is more likely to result in foot pain for older adults, which may lead to an increase in the risk of falling (Mickle et al., 2010a). Other studies have emphasised that foot pain is associated with the pressures distributed under the foot during gait (Burns et al., 2005; Hodge et al., 1999; Jannink et al., 2006).

A study by Jannink et al. (2006) was conducted to evaluate the effectiveness of adopting custom-made orthopaedic shoes in reducing foot pain and plantar pressure for people with degenerative disorders of the foot. There was a significant correlation between foot pain during gait and the mean pressure generated under the second and third metatarsal bones. The results revealed that these shoes significantly decreased foot pain by about 23%. The results also demonstrated that using these shoes significantly decreased the amount of pressure beneath all plantar regions by 9%.

It has been documented that gait bio-mechanics and balance alter with advancing age (Kressig et al., 2004; Winter et al., 1990). It has also been evident that foot complaints have been associated with balance impairment and have increased the risk of falling for older people. For instance, the existence of hallux valgus and lesser-toe deformities has been found to exhibit moderate to weak relationships with functional test scores and balance undertaken for one hundred and seventy six subjects of mean age 80.1 years. The study suugested that toe deformities are likely to cause a decline in human functional mobility (Menz et al., 2005d). Mickle et al. (2009b) have emphasised that the above two foot problems are prevalent in the older community and have associated them with an increase the risk of falling among people of this age. This fact has also been highlighted by another study conducted by Mickle et al. (2009a).

Hallux valgus foot disorder is common in older adults, reaching to 74% in its prevalence rates according to numbers recorded in both institutional and clinical settings (López et al., 2016). This foot disorder is a progressive condition of deformity of the first metatarsophalangeal joint, resulting in a lateral deviation of the hallux (Thomas et al., 2003). People with hallux valgus foot deformity have been shown to have increased mean peak pressure values under first, second, and third metatarsal head sites accompanied by increased contact time for the stance phase of the gait cycle under normal walking conditions (Martínez-Nova et al., 2010; Mickle et al., 2011a; Nix et al., 2013; Plank, 1995).

A number of studies have been conducted to investigate the hallux valgus foot deformity that is common in older people (D'arcangelo et al., 2010; López et al., 2016; Menz et al., 2011; Nguyen et al., 2010; Nix et al., 2010). This condition may be linked to impairment of body balance, increased risk of falling, and gait instability, particularly during when walking on irregular surfaces (Menz et al., 2005a; Mickle et al., 2009b; 2011a). Therefore, higher peak plantar pressures located under the forefoot and hallux regions, adopted as a measurement parameter in the above mentioned studies, can potentially be utilised as a preliminary predicted sign to develop this foot condition, which can be a clinically significant observation (Plank, 1995).

In a sample of three hundred and twelve community-dwelling older males and females, aged above 60 years, used for studying the effects of toe deformities on the gait, balance, and plantar pressure, the distribution of loading patterns was implemented. Plantar pressure measurements were captured using an Emed-AT4 pressure system. The subjects were asked to perform the two-step gait initiation protocol for the collection of their plantar pressure distribution measurements. The two-step gait protocol was selected due to the foot conditions of the participants. The protocol was found to produce an adequate measurement (van der Leeden et al., 2004). The findings revealed that older people with hallux valgus and lesser-toe deformities had shown an alteration in load distribution under the forefoot area, suggesting that these changes may in turn impair the gait and body balance with increasing human age (Mickle et al., 2011a). Figure 2.5 displays the ten plantar regions selected in the study. Most of the regions in focus were under the forefoot area because of its relation to the hallux valgus and lesser-toe deformities. Their corresponding peak plantar pressures and pressure-time integrals under the metatarsal heads, hallux, and lesser toes areas appear in Figures 2.6, and 2.7, respectively.

As it has mentioned earlier, the function and structure of the ankle and foot are likely to be altered due to aging. A study by Mickle et al. (2011b) aimed to investigate the plantar soft tissue thickness associated with aging, in particular whether the thickness of the tissue under the five metatarsal heads for two older groups, with and without the presence of toe deformities, was different. The results exhibited a significant reduction in the plantar soft tissue thickness at the first metatarsal head for older individuals with hallux valgus compared to the control group. Furthermore, the findings revealed a significant reduction of the total plantar soft tissue thickness under the fifth metatarsal head for older individuals with lesser-toe deformities compared to the control group.

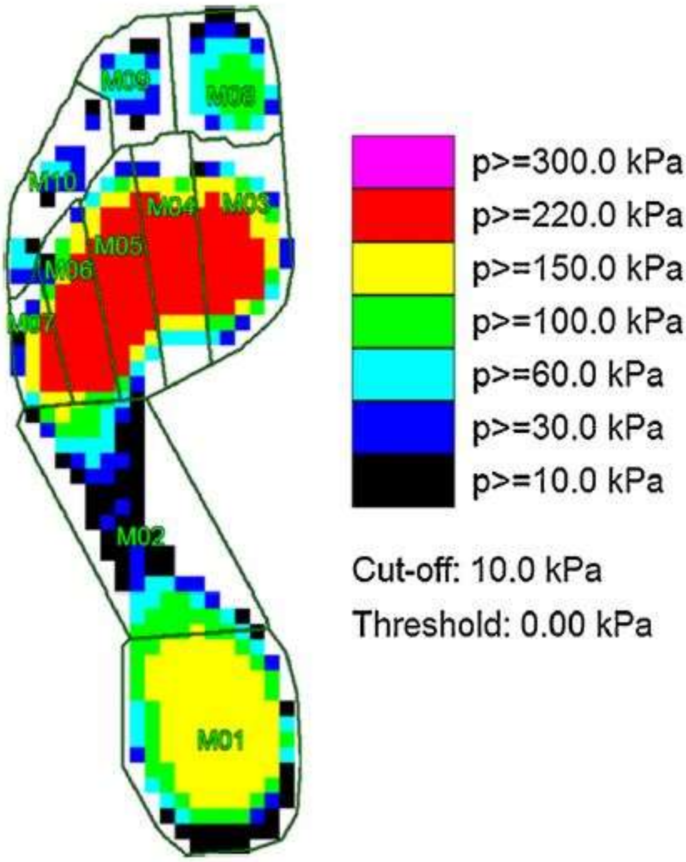

Figure 2.5: A mean peak pressure image showing the ten masked plantar regions: heel (M01), mid-foot (M02), metatarsal 1 – 5 heads (M03 – M07), hallux (M08), second toe (M09), and toes 3 – 5 (M10). The color scale indicates the maximum pressure distributed in each sensor (Mickle et al., 2011a).

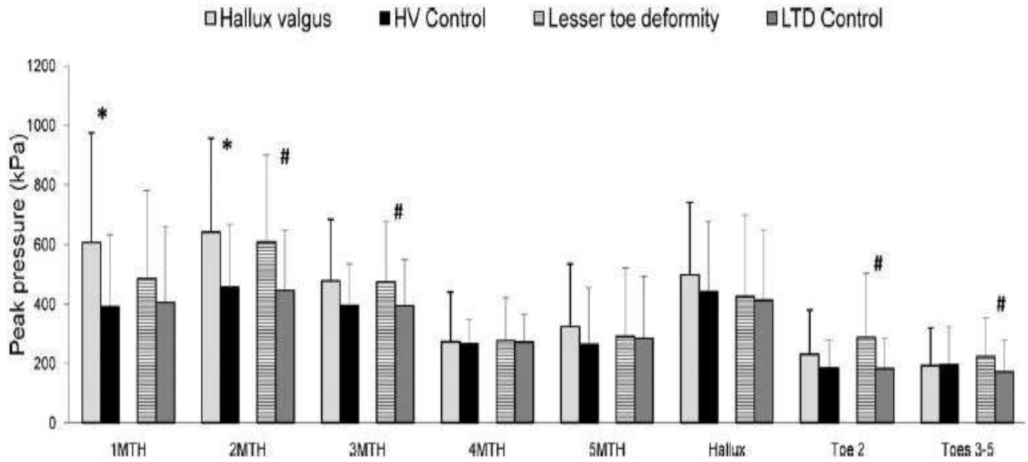

Figure 2.6: Mean and standarad deviation values of peak plantar pressure for the hallux valgus (HV), lesser-toe deformity (LTD), and control groups measured under the five metatarsal heads, the hallux, second toe, and toe 3 – 5 area.

* indicates a significant difference between HV group and their matched controls.

# indicates a significant difference between LTD group and their matched controls, (Mickle et al., 2011a).

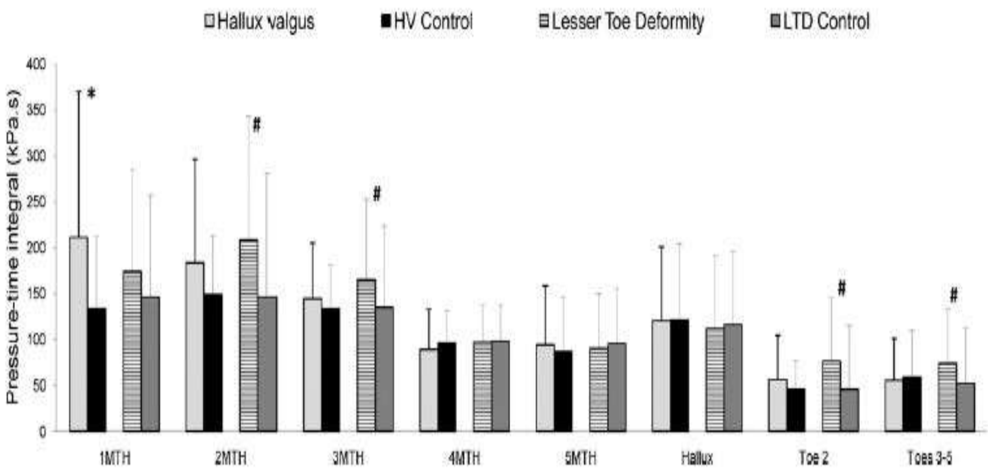

Figure 2.7: Mean and standard deviation values of pressure-time integral for the hallux valgus (HV), lesser-toe deformity (LTD), and control groups measured under the five metatarsal heads, the hallux, second toe, and toe 3 – 5 area.

* indicates a significant difference between HV group and their matched controls.

# indicates a significant difference between LTD group and their matched controls, (Mickle et al., 2011a).

Apparently, the presence of hallux valgus, lesser-toe deformities, and the atrophy of the plantar soft tissue, which are prevalent in adult people, and are more likely to increase with increasing human age, affects the forefoot area. One study conducted on white people from both genders, mean aged 66 years documented that the above three foot disorders have found to be increased in older groups aged 61 – 80 years.

It is worth noting that the hallux valgus foot deformity affects the forefoot area for patients of this disorder, resulting in the development of forefoot pain for older people (Dunn et al., 2004; Menz, 2016; Menz and Lord, 2001; Menz et al., 2005b). Forefoot pain has been associated with abnormal patterns of plantar pressure parameters (Waldecker, 2002). In a study of a number of older people, aged 62-96 years using a floor-mounted resistive sensor mat system, plantar pressures and forces were measured (Menz et al., 2006a). The aim of the mentioned research was to evaluate the relationships between a number of clinical tests of the foot and ankle, including foot pain, with the force and pressure values measured under the foot. These relationships might explore clinical interventions for plantar pressure related to foot problems sustained with advancing age (Menz and Morris, 2006a).

It is important to mention that progression of the hallux valgus condition can result in further foot disorders, especially hammer deformities (Thomas and Barrington, 2003). Hammer toe disorder is a deformity of the metatarsal phalangeal joint occurring in patients with a history of ulcerations. This foot deformity is characterised by decreasing the loading under the toes area along with increasing the loading at the metatarsal heads, resulting in higher amounts of peak pressures distributed under the metatarsal heads region. Elevated peak pressure was found to be associated with skin break down (Ahroni et al., 1999; Cavanagh et al., 1997; Mueller et al., 2003). Hammer toe deformity is prevalent in women with advancing age (Ellington, 2011), which may sometimes necessitate the removal of the second toe due to severe pain caused by this deformity among older people (Gallentine et al., 2005).

As it has been mentioned earlier, plantar pressure distribution has been widely used as an evaluation approach for various foot complaints. Because the loading on the metatarsal heads is occasionally increased as a result of specific foot conditions such as hallux valgus and hammer toe deformities, a metatarsalgia could develop. In metatarsalgia, the hallux region undergoes a functional impairment, leading to simultaneously transferring the loading from this region to the metatarsal heads with poor loading distribution (Waldecker, 2002). A study by Waldecker (2002) aimed to measure plantar pressure patterns for patients with the condition of hallux valgus, with and without metatarsalgia symptoms to find out the pressure variations, which are anticipated to be the reason for developing metatarsalgia conditions. The plantar pressure measurements were collected using capacitive pressure platform systems with the two-step gait initiation as a walking way protocol. The results revealed significantly higher loading patterns, including peak pressure and pressure-time integral at the lateral forefoot region for a group with metatarsalgia compared to the other group. Figure 2.8 shows the peak pressure values under the lateral forefoot area for both participating groups: group (A) for patients with hallux valgus and symptoms of metatarsalgia, and group (B) for patients of asymptomatic hallux valgus feet. Furthermore, hallux valgus may lead to subluxation of one of the metatarsophalangeal joint, resulting in severe condition of metatarsalgia. Those patients may require the removal of the corresponding metatarsal head because of the severity of this painful condition (Raymakers et al., 1971).

In the literature, it has been stated that forefoot deformities can lead to the development of metatarsalgia as a result of elevated plantar pressures distributed at the metatarsal heads (Keijsers et al., 2013). Keijsers et al. (2013) found that an increase in peak pressure and pressure-time integral magnitudes at the second and third metatarsal heads often led to forefoot pain. Forefoot pain can result in reducing physical activities, leading to an increase in the risk of falling encountered by older adults. Hence, a study conducted by Chang et al. (2014) investigated the effectiveness of adopting an accommodative insole for the redistribution of plantar pressure measurements for twenty-one older adults diagnosed with metatarsalgia. Plantar pressure parameters were measured using Pedar-X systems. It was found that there was a significant decrease in peak pressure at the metatarsal heads by about 47% and the pain scores were reduced from 8.2 to 1.1. The study indicated that using accommodative insoles can relieve the symptoms of metatarsalgia, thereby preserving daily walking activities for older adults with metatarsalgia. Another study evaluated the use of two podiatric protocols for patients of metatarsalgia. The results pointed out that the contact area under the foot was increased along with decreasing the plantar pressure measurements for patients of metatarsalgia while performing these protocols (Bongi et al., 2014).

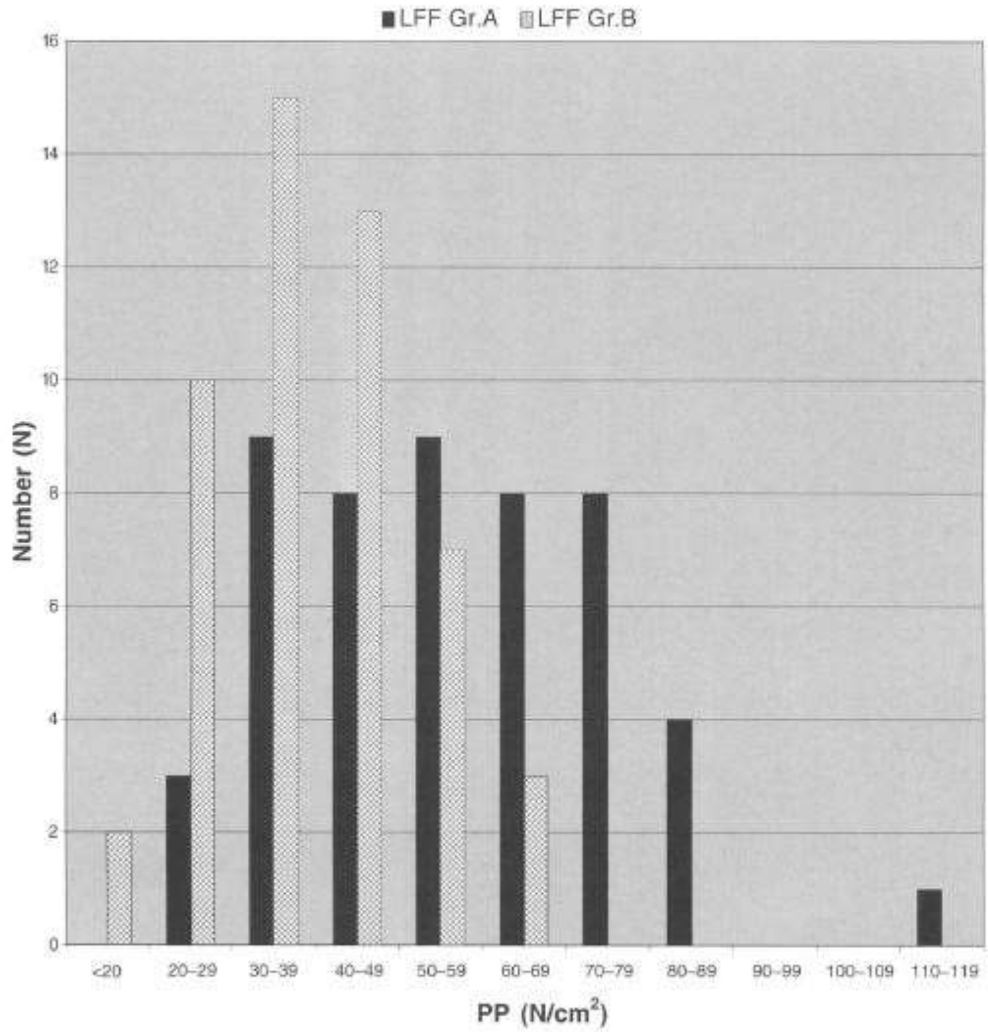

Figure 2.8: Peak pressure distribution for group A (patients with hallux valgus accompanied by metatarsalgia symptoms) and B (asymptomatic hallux valgus feet). PP: peak pressure, LFF: lateral forefoot, (Waldecker, 2002).

A number of studies in the literature have investigated metatarsalgia in terms of the number of people having this foot condition with relate to aging factor, the treatments and strategies to relieve the pain-related metatarsalgia, and the association between metatarsalgia and the poor distribution of the plantar measurements at the metatarsal heads (Federer et al., 2018; Hackney et al., 2010; Kang et al., 2006; Keijsers et al., 2013; Naraghi et al., 2014; Thomas et al., 2009; Tovaruela-Carrión et al., 2018).

The measurement of plantar pressure during gait or other functional activities can demonstrate the mechanics of the abnormal pathological foot. It can also create the objective measures essential to evaluate specific disease progression (MacWilliams et al., 2000; Saggin et al., 2013). Obesity and overweight have been considered as risk factors for the development of multiple chronic illnesses (Bray, 2004). It has been shown that body weight is more likely to steadily increase with increasing human age (Hajek et al., 2020; Mensink et al., 2013). Obesity has been associated with foot pain and other foot disorders as indicated by a number of recent studies (Butterworth et al., 2012; Butterworth et al., 2016; Dufour et al., 2017; Hill et al., 2008; Menz et al., 2011; Mickle et al., 2015). Other recent studies have associated obesity with reduced balance control, resulting in an increased risk of falling in community-dwelling older people (GR Neri et al., 2020; Melzer et al., 2016; Neri et al., 2020a; Neri et al., 2020b; Neri et al., 2019; Neri et al., 2018).

Additionally, obesity has been associated with altered plantar pressure distribution in the older community. (Dufour et al., 2017; Mickle and Steele, 2015). The association between obesity and an alteration in plantar pressure patterns in older women was investigated by Neri et al. (2017). The study adopted an Emed AT-4 pressure measurement platform system to analyse the values of peak plantar pressure during gait for those participants. It was found that obese women showed higher peak pressure measures under the mid-foot region compared to women with normal weight and overweight conditions. In addition, overweight women showed higher peak plantar pressure values at the mid-foot area relative to subjects with normal weight. The results also exhibited higher plantar pressure values at the forefoot area for obese women compared to those of normal weight. The association between obesity and elevated plantar pressure values under the mid-foot area was emphasised through a study undertaken by Walsh et al. (2017), who aimed to explore the relationship between increasing human body weight and the redistribution of plantar pressure and foot pain. Plantar pressure measurements were collected using Tekscan Matscan pressure platform systems. The results revealed a significant association between the changes in human body weight and the changes in plantar pressure values at the mid-foot area. The study suggested that increasing human body weight has an influence on foot-related pain and the functional limitation, which may develop as a result of elevated plantar pressure under the mid-foot area. Obese people have shown to present with flatter foot and elevated peak plantar pressure values during gait compared to non-obese people according to research conducted by Butterworth et al. (2015). This study highlighted that increasing body weight was associated with higher plantar pressure loading, in particular at the mid-foot and forefoot regions, which may increase the stresses under these regions for obese patients (Butterworth et al., 2015). The higher peak pressure values observed at the plantar surface for obese people compared to non-obese were reinforced by Hills et al. (2001). Increasing the loading on the plantar tissues could lead to plantar damages and injuries (Mickle and Steele, 2015) thereby reducing daily physical activities. Elevated plantar pressure for obese older adults during walking has been proven to increase foot pain and increase the risk of falling sustained by this age stage(Mickle et al., 2010a).

To our knowledge, there are limited chances to study the differences in plantar pressure distribution during gait between healthy older adults and adults. Few studies have investigated the variations of dynamic plantar pressure distribution between young with older and elderly people using a variety of systems. Plantar pressure values were compared for thirty-five young adults aged 18-24 years, and thirty-five elderly subjects aged 71-90 years adopting capacitive platform systems. The pressure pattern for barefoot gait was assessed beneath seven foot regions. The findings showed that the region at the first metatarsal head yielded higher peak pressures for elderly subjects than those of young adults, whilst the elderly subjects recorded lower peak pressure measures at the mid-foot region than the young adults (Kernozek et al., 1995). In a sample of nine young and six elderly subjects using shoe insoles of 99 capacitive sensors each as a measurement system, foot loading was captured at their normal walking speed on the treadmill. Forces and pressure values were measured underneath nine plantar regions. The findings revealed that elderly people had more weight bearing on their plantar lateral side than young subjects, which can affect the balance and limit the walking ability for elderly subjects (Hessert et al., 2005b). Furthermore, twenty adults, aged 55-85 years were involved in a research to identify the impact of walking velocity and footwear conditions in eight foot regions on the plantar pressure variables. The results pointed out that higher plantar pressure values for selected subjects were associated with barefoot and faster walking conditions (Burnfield et al., 2004).

Although gait impairment and maintaining the balance during loading phases of gait are of particular interest due to their association with increasing human age as indicated by a number of previous research (Lord et al., 2007; Menant et al., 2008; Rubenstein, 2006; Sturnieks et al., 2008), relatively few studies have investigated the normal walking for healthy older adults, and the difference of their normal gait to the corresponding adults' group, thereby providing comprehensive insights into plantar pressure pattern variations, in the two cohorts. Therefore, it has been suggested in this investigation to understand the plantar pressure pattern comparisons between adult subjects and the older adults, prior to reaching the elderly stage with a deterioration in their conditions in terms of maintaining healthier foot plantar. In addition, a range of pressure parameters measured under normal walking at self-selected speed condition analysed for older adult subjects could be used to form a reference value to be compared when investigating various pathological cases in clinical settings encountered by older people, of an age similar to that of the group being explored in the current work. A substantial amount of the work provided in this research will be assigned to evaluate the plantar pressure patterns between the two participating cohorts: older adults and adults, while moving. These comparisons will be demonstrated in detail in chapter three using F-scan sensor insoles, and in chapter five for the evaluation of dynamic barefoot plantar pressure patterns using floor-based pressure mat platform systems. The following section will present the plantar measurement systems, particularly the ones which were adopted in the present study and their relevant literatures.

2.6 Plantar pressure measurement systems

Plantar pressure measurement systems have become a research tool that is important in gait analysis as these electronic devices are able to measure the pressure distributed between the human foot plantar with the interacted supporting surfaces during locomotion (Abdul Razak et al., 2012; Martinez-Nova et al., 2008; Noce, 2005; Perttunen, 2002). The plantar pressure distribution between the human foot and the ground has become of particular interest through the provision of valuable information with regard to the function and structure of the human foot (Gerber, 1982; Morag et al., 1999; Ranu, 1986; Scott et al., 2007). The pressure systems can measure the interaction of human barefoot and the ground, the sole of the shoes and the ground, and the insole of the shoes with the human plantar surface (Lord, 1981; Perttunen, 2002). The pressure measurement systems include pressure sensors typically designed to measure the plantar parameters for subjects and patients without disturbances (Noce, 2005; Rodrigo et al., 2013). Furthermore, plantar pressure systems have proven to be useful in various fields, including clinical gait studies, footwear design assessment, foot pathologies diagnoses, and in biomechanics and sports usages (Abdul Razak et al., 2012; Bergstra et al., 2015; Ramirez-Bautista et al., 2017; Sobhani et al., 2017; Song et al., 2015). In addition, plantar pressure measurement systems have been effectively used to measure plantar parameters for both static and dynamic conditions (Abdul Razak et al., 2012).

However, plantar pressure measurement systems undergo some limitations. For instance, the pressure measured in each sensor is calculated based on the force value acting on that specific sensor when the foot is in contact with any supporting surface instead of relying on the resultant force that can be obtained from the force platform systems. Then, the pressure is determined as the measured force divided by the area of that sensor (Orlin and McPoil, 2000). The other components of the ground reaction force are crucial to study the development of plantar ulcers for people with diabetes (Orlin and McPoil, 2000).

According to a study undertaken by Abdul Razak et al. (2012), there are two basic types of measurement systems employed for plantar pressure distribution, comprising platform systems and in-shoe systems. Both of these will be utilised in the present study. A study conducted by Chevalier et al. (2010) evaluated the pressure measurements using different plantar pressure methods, including F-scan for in-shoe measurements and Matscan systems for shod and unshod plantar pressure distribution. The plantar parameters included peak force and pressure values, timing calculations, and the centre of pressure excursions, were collected from twenty-one adult subjects using a two-step gait protocol under three regions, namely rear-foot, mid-foot, and forefoot. The data measured by different methods showed relative variations with the in-shoe condition presented the highest peak force values. Furthermore, the highest peak pressure findings were detected from the shod condition captured by a Matscan method. The study suggested that the data from each collection method have their own specific standard measurements (Chevalier et al., 2010).

2.6.1 Platform pressure mat systems

Platform mat systems consist of a matrix of pressure sensor elements configured to be embedded with the ground, thereby enabling non-intrusive barefoot measurements due to their thinness. These systems are ideal for both static and dynamic measurements, including a number of plantar parameters: vertical ground reaction force and pressure acting on the foot sole (Abdul Razak et al., 2012; Noce, 2005; Orlin and McPoil, 2000; Rodrigo et al., 2013). The platform mat systems are stationary, thin, and flat so they are easy to use while capturing plantar measurements (Abdul Razak et al., 2012). However, they are restricted for use as research tools in laboratories. Furthermore, the subjects are required to be familiar with walking on the floor mat to ensure acquiring natural and realistic measurements; for example, the foot should contact the centre of the mat to yield an accurate plantar pressure distribution (Hurkmans et al., 2003; MacWilliams and Armstrong, 2000). These systems have another drawback with regard to the number of steps required for measurements. It is necessary to collect the plantar data for multiple steps for obtaining a representative profile related to the foot as suggested by the studies conducted by Hughes et al. (1991), Urry (1999), and in a review study, to measure the weight bearing in both standing and walking conditions, undertaken by Hurkmans et al. (2003). These studies have emphasised the necessity to obtain at least three plantar measurements (MacWilliams and Armstrong, 2000), particularly when the research focus is to compare between various subjects belong to different groups. Consequently, it is a fundamental principle to repeat the gait test by asking the subjects to walk on the pressure mat several times. Figure 2.9 displays a platform pressure mat system.

As it is essential to obtain adequate pressure measurements for both research and clinical contexts, some studies evaluated the accuracy of the resistive technology by Tekscan systems. A study undertaken by Giacomozzi (2010) revealed that high accuracy measurements were obtained from Tekscan technologies with root mean square error of less than 2.5% of the research outcomes. In another investigation to evaluate the reliability of the Tekscan Matscan systems for the plantar force and pressure measured during normal barefoot walking for thirty adult subjects, the study demonstrated moderate to good level of reliability, exhibiting similar reliability with other commercial plantar systems. Consequently, the Tekscan Matscan systems were found to be suitable in both research and clinical settings (Zammit et al., 2010).

Plantar pressure techniques can provide dynamic loading assessment of the foot in addition to the provision of the information about the loading at each region making contact with the ground. A study by Cousins et al. (2012) investigated the reliability of plantar pressure data in forty-five children during barefoot level gait conditions performed in two sessions using Matscan pressure platforms. Peak force, peak pressure, force-time integrals, and pressure-time integrals were analysed under seven anatomical foot regions. Within-session, the results demonstrated moderate to good reliability levels for the three gait trials under all selected regions, except the lesser-toes area. For between-sessions, the results revealed good reliability levels across all plantar regions except the lesser-toes area, which exhibited moderate reliability levels assessed by using Intraclass Correlation Coefficients (ICC). Based on the study conducted by Cousins et al. (2012), reliable plantar loading measurements can be obtained using Tekscan Matscan platform techniques.

It is worth noting that platform based-pressure measurement systems can be used to measure plantar loading while the subject is wearing shoes (Rosenbaum and BECKER, 1997); however, this condition cannot provide information with regard to the actual loading of the foot structure. Therefore, the platform systems are more suitable to measure the loading patterns while the subjects are in the barefoot condition for the evaluation of their foot function. For instance, the investigation of the foot function for injured subjects can be completed by comparing it with the loading patterns for healthy individuals. Hence, the platform systems are not appropriate to evaluate the properties of footwear designs or study the effects of different orthotics (Rosenbaum and BECKER, 1997).

Based on the above discussion, it was suggested that a Tekscan Matscan pressure system should be used to capture plantar pressure parameters during gait while the subjects were barefoot. It is intended that the plantar loading measurements would be captured under fifteen plantar regions during five phases included in the stance phase of the gait cycle: heel-strike, foot-flat, mid-stance, push-down, and toe-off phase. This work will be displayed in chapter five. In addition, the pressure data captured by a Tekscan Matscan pressure system will be integrated, with the human movement data captured and analysed using photogrammetric techniques. This work will be displayed in chapter six.

Figure 2.9: Platform mat systems, picture adopted from the website of Tekscan pressure mapping, pedobarography systems for plantar pressure measurement.

2.6.2 In-shoe pressure pad systems

There is a need for efficient, accurate, and low-cost pressure sensor systems in clinical, research, and sport gait analysis. Many studies have used in-shoe pressure measurement technologies for pressure distribution evaluation under the human foot, which can be essential for precise assessment of the functional foot and gait-related pathologies (Forghany et al., 2018; Mao et al., 2006; Martinez-Nova et al., 2008; Putti et al., 2007; Qin et al., 2015). The accuracy and repeatability of the insole systems have been proven through a number of previous studies (Hurkmans et al., 2006; Kernozek et al., 1996; Ramanathan et al., 2010). Among the most popular in-shoe pressure systems are F-scan and Pedar, which are used by many researchers.

In-shoe pressure sensors can inherently record multiple successive steps in order to study the variability between steps (Akhlaghi et al., 1994), thus overcoming the limitation of obtaining one step measurements by each gait trial performed via the platform system. This can also explain the diverse usage of the insole based-pressure systems (Akhlaghi et al., 1994; Hughes et al., 1991; Urry, 1999). Multiple steps can be analysed with one gait test by insole systems, and therefore can be useful for the foot assessment in sport or work environments in order to find out the causes of foot complaints for people with overload problems (Rosenbaum and BECKER, 1997).

Furthermore, in-shoe systems are able to detect the plantar pressure distribution between the plantar and the shoe; as a consequence, the construction of different shoe designs and the evaluation of various orthotics can be assessed directly by these systems through the plantar-shoe interface (Perhamre et al., 2011; Rosenbaum and BECKER, 1997). In one study to evaluate the effectiveness of adopting functional insoles on plantar force and pressure values measured during race walking for walkers experiencing overuse injuries, twenty race walkers were recruited. Each subject performed the race walking once wearing normal insoles and then functional insoles. The findings revealed that using functional insoles decreased the peak pressure under metatarsal heads and heel areas, suggesting that these insoles can reduce the lower limb injuries risk (Song et al., 2015). An investigation conducted by Tsung et al. (2004) evaluated the effectiveness of using different insoles on plantar pressure redistribution during gait for diabetic patients compared with the control healthy group. F-scan insoles were used to capture and analyse plantar pressure patterns for three plantar supports: with shoe alone, with flat insole, and with insoles designed based on casting the plantar of the subjects' foot under different weight-bearing conditions. The corresponding results exhibited a reduction in localised pressure parameters accompanied by increasing the contact area while the subjects wore flat insoles and contoured insoles, compared with wearing only shoes. The results also pointed out a better reduction in localised peak pressure values while the subjects were wearing contoured insoles rather than flat insoles.

In-shoe pressure insoles can provide a visualisation of the temporal characteristics under the plantar surface while undertaking weight bearing tasks (Spooner et al., 2010). Additionally, using pressure insoles permits the measurement of the plantar parameters of the human foot during various functional and environmental activities (Mueller et al., 1996). Pressure insoles can assist in the provision of plantar pressure distribution beneath the entire foot plantar with high reliability (Kernozek et al., 1996; Putti et al., 2007), and observe a number of plantar lengths and the existence of a number of toe deformities (Morag and Cavanagh, 1999). Providing this information can be beneficial in pathological diagnoses (Orlin and McPoil, 2000).

It has been shown that the F-scan insole is one of the most frequently used, as it can be attached to the human body for the purpose of plantar pressure distribution acquisition for both research and clinical fields (Ramirez-Bautista et al., 2017). The F-scan insole is resistive sensor technology, which is extremely thin, only 0.15 mm. Each insole includes two sheets of polyester with an electrical circuit printed at the inner side of both surfaces. There is a semiconductive ink inserted between the electrical circuits. Based on the pressure applied, the electrical resistance of a semiconductive ink changes inversely in proportion to that pressure. The F-scan pressure insole contains 960 pressure sensing locations with four sensors per cm^2 as its spatial resolution, and 345 – 517 kpa as a pressure range (Chevalier et al., 2010; Hida et al., 2017; Hsiao et al., 2002; Kim et al., 2013b; Ramirez-Bautista et al., 2017), as appears in Figure 2.10, and Figure 2.11. The F-scan sensor is undetectable inside the shoes because it is thin so it does not interfere with the individual’s normal gait.

Additionally, the F-scan sensors have been identified as a cost-effective, efficient and reliable system for plantar pressure measurements (Ahroni et al., 1998; Hida et al., 2017; Mueller and Strube, 1996; Razak et al., 2012). The in-shoe F-scan sensor is flexible as it is portable, allowing a broad variety of research to be performed, including various gait tasks in different environments and multiple footwear designs. These sensors are embedded into the subject’s shoes; hence, they will eventually reflect the plantar pressure measurements based on the interface between the foot plantar and the shoe (Razak et al., 2012).

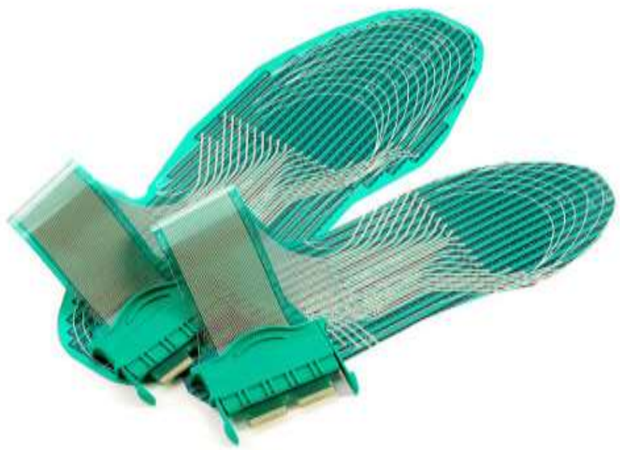

Figure 2.10: F-scan pressure insoles, picture adopted form the website of Tekscan company (Tekscan, South Boston, MA, USA).

Figure 2.11: F-scan pressure insoles systems attached to human lower limb, picture adopted form the website of Tekscan company (Tekscan, South Boston, MA, USA).

One of the limitations of using F-scan insoles is their limited durability as a result of possible damage from repeated gait tests and the high pressure applied, accompanied by successive uses (Cavanagh et al., 1992; Woodburn et al., 1996). However, F-scan insoles are designed as disposable materials (Hsiao et al., 2002), so this limitation may not apply.

Hence, based on the above mentioned discussion, it was suggested to adopt an in-shoe 3000E F-scan® pressure sensor (Tekscan, Boston, MA) system sampling at 100 Hz for capturing plantar parameters: contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral in the current study, particularly when older people are the main study participants, thereby reflecting reliable gait patterns for this age group. The F-scan sensors have been adopted in our research to identify the specific range of plantar pressure values distributed in healthy older adults and adult subjects. This will be demonstrated in chapter three. In addition, variations in plantar pressure patterns for a number of older people during various functional activities, including normal walking on level surfaces, and uphill and downhill walking tasks using F-scan sensor insoles were evaluated. This work will be presented in chapter four. The sensor sheet was precisely taped with the shoe sole so there is no possibility for the sensors to slip while performing the gait, enabling the achievement of a reliable measurement (Razak et al., 2012). The insole pressure system was calibrated before the gait test for each subject in advance based on manufacturer's guidelines.

2.7 Gait trial requirements while collecting plantar pressure measurements

In the context of finding the required number of gait cycles to be performed by individuals while collecting their plantar pressure distribution measurements, a number of data collection techniques are used which might have an impact on plantar pressure patterns. Stewart et al. (2016) conducted research to identify gait parameters and the distribution of foot plantar pressure during barefoot walking in order to make a comparison of findings from the participants with gout and participants with asymptomatic hyperuricemia with healthy individuals who have normal serum urate concentrations. In that research, the participants had an instruction to familiarise themselves with the gait protocol so that their second step was in the sensing area. Furthermore, in order to ensure that acquired pressure data reflected participants' normal gait, participants were asked to walk as their normal walking speed and keep walking after the sensing area for at least two more steps.

Chong et al. (2015) described the approach in which the plantar shape and the pressure image during walking were matched by adopting markers. These markers were placed on the plantar surface, thereby identifying their positions on the pressure image. The participants were instructed to perform the protocol to ensure obtaining a steady-state gait. The protocol required that three-steps should be completed before reaching the floor-mat for eventually landing the foot on the sensing area to capture the corresponding plantar pressure data. A research was conducted by Chong et al. (2014) for matching the dynamic 3D model, which was captured by photogrammetric techniques, the ground reaction force and the pressure data which were recorded during the loading phase of gait. During the gait trial, the subjects were instructed to perform three-step normal walking across a force plate one time and across the pressure mat another time, while video clips captured the whole plantar surface. These video clips were utilised to identify the match between the plantar model and the force and pressure data during the loading phase of gait.

Bus and de Lange (2005a) presented a barefoot plantar pressure measurements for the evaluation of the ulceration risk for patients with diabetes and neuropathy. The aim of the research was to make a comparison between three common step-protocols (one-step, two-step and three step) adopted for plantar assessment of fourteen diabetic neuropathic patients. From the findings of the research, it was apparent that to obtain reliable pressure data in terms of minimal number of repeated trials, the two-step protocol was recommended for assessment of these patients (Bus and de Lange, 2005a; McPoil et al., 1999; Perttunen, 2002).

Taylor et al. (2004) discussed how changes in the speed of participants' walking impact the plantar pressure measurements utilising the protocol of two-step gait. From the research findings, it was apparent that various walking speeds influence the pressure-time integrals at most regions under the foot; for instance, the pressure-time integrals were diminished at faster walking speeds. On the other hand, various walking speeds had no significant influence on the magnitude of plantar pressure values. A study to compare the reproducibility of plantar pressure measurements for three step protocols (one-step, two-step and three-step) was conducted in patients with Chronic Arthritis in order to estimate the required number of measurements. This study, which was conducted by van der Leeden et al. (2004), involved calculating the first three, five and seven measurements for patients' feet to determine the consistent average of required number of measurements. It was apparent that the two-step protocol required three measurements in which it was sufficient to obtain a consistent average. Consequently, the two-step protocol was considered to be less time consuming which was helpful for patients suffered from painful feet.

Menz and Morris (2006a) recorded plantar pressure measurements for defining clinical determinants of foot and ankle characteristics that could explain the difference in pressure patterns during walking in older people. The study adopted the two-step gait protocol for obtaining plantar pressure measurements under seven regions of the foot. Use of the two-step gait protocol was found to be adequate for ensuring reliable plantar pressure measurements with only three trials of data collection. Normal measures of plantar pressure distribution were determined using the Emed-SF system through a study undertaken by Bryant et al. (2000). The authors of the study have adopted the two-step gait protocol for the provision of these data sets. In addition, the two-step gait initiation protocol was used by another research, which was conducted by Zammit et al. (2010) to investigate the reliability of Tekscan plantar pressure platform systems during barefoot normal walking on level surfaces to evaluate the gait patterns for a number of healthy adults.

To sum up, the two-step gait protocol was found to have similar reliability with the mid-gait step protocol with fewer required number of gait trials (Bryant et al., 1999; Oladeji et al., 2008). Three gait trials were found to be sufficient for adequate reliability as discussed by a number of previous research (Hughes et al., 1991; McPoil et al., 1999; van der Leeden et al., 2004). Furthermore, the two-step gait initiation was proven to be efficient and reproducible protocol for the evaluation of plantar pressure distribution than the other two protocols (one and three steps), particularly for people experiencing foot complaints. Therefore, a number of age-related plantar pressure distribution investigations adopted a two-step gait initiation protocol as a collection way for their research plantar measurements (Menz et al., 2010; Mickle et al., 2010a; Mickle and Steele, 2015).

Therefore, in this project, the individuals were asked to perform a two-step gait initiation protocol with normal gait across the pressure mat to ensure ultimately reliable barefoot plantar pressure measurements with a limited number of trials. Hence, before the gait trial, the subjects were given few minutes to practise the procedure in which plantar pressures are obtained on the second step when the foot lands on the pressure mat using Tekscan Matscan as a barefoot-based pressure measurement system for the two participating groups: older adults and adults. In the meanwhile, the video clips captured the whole lower limb and foot for the individuals during the gait via a photogrammetric system involved in the current study.

2.8 Plantar loading assessment of exercise and sport-related activities

For studies related to sport medicine, serious injuries are likely to be incurred by the lower extremity by various worldwide sport activities (Losito, 2017). These sports involve multiple movements performed in various directions (Abdelkrim et al., 2007), which can lead to the development of plantar stress-related damages and injuries. Therefore, it is essential to understand the loading demands in relation to the movements required by sport activities. Plantar pressure measurements have been predominantly used to investigate various shoes and shoe soles to assist those players.

The assessment of regional plantar pressure across a range of movements may assist in the provision of a reasonable evaluation of the performance of various sport shoes (Orendurff et al., 2008). The hardness of the shoe midsole was examined to study its influence on plantar pressure distribution for various movements involved in the basketball. The study examined twenty basketball players while wearing hard and soft midsole of customised shoes. Peak pressure and pressure-time integral values were extracted from four basketball-related movements in ten plantar regions. The results exhibited lower peak pressures and pressure-time integrals measured in a number of foot regions across the four selected movements while the players wearing soft shoes were compared to hard shoes findings. The study recommended that the soft midsole can be considered as a plausible solution to reduce the excessive plantar measurements experienced by basketball players (Lam et al., 2017).

Furthermore, the choice of appropriate shoes can reduce loading patterns, which are the underlying reason to injuries due to overuse during daily running activities. Two types of shoes: training and racing flat were adopted by research to determine the gender-related variations in plantar patterns during running activities. Pedar insoles were used to measure contact area, maximum force, and contact time values for thirty-four subjects under the whole foot and eight foot regions (Queen et al., 2010). The findings exhibited a reduction in the contact area parameter at the whole foot, medial mid-foot, and medial forefoot accompanied by an increase under the lateral forefoot area while both gender wearing the racing flats. For both types of shoes, the men's results pointed out a reduction in contact area values under both medial and central forefoot regions and an increase under the lateral forefoot region. The increase in the lateral forefoot contact area for men was accompanied by a significant increase of the maximum force values, suggesting that the lateral forefoot area, particularly in men while wearing racing flats, is one of the most vulnerable parts for the risk of stress fracture. The study recommended that, based on the research loading patterns outcomes, running shoes should be designed with the consideration of gender-specific requirements to prevent possible overuse injuries related to running activities (Queen et al., 2010). A number of recent studies have also investigated the influence of various footwear designs in relation to multiple sports (Cui, 2010; Lam et al., 2019a; Lam et al., 2019b; Werd et al., 2010; Wong et al., 2007). These studies were used different footwear designs to evaluate the gait patterns for subjects during different sport activities. The studies emphasised that appropriate footwear designs in relation to the needs of specific sports are necessary for reducing the foot injuries due to overuse while performing these activities.

2.9 Footwear association with altered plantar pressure distributions

Generally, changes in foot structure commonly occur with advancing age. These changes include flattening of the foot, a reduction in the thickness of plantar fat pad, and the development of a number of foot deformities (Chaiwanichsiri et al., 2009; Menz, 2008; Mickle et al., 2009b; Myerson et al., 1989; Scott et al., 2007). Regardless the fact that age-related changes in foot structure influence of the redistribution of dynamic plantar pressure measurements (Buldt et al., 2018; Menz et al., 2010; Scott et al., 2007), footwear can play a fundamental role in the plantar pressure redistribution for older people (Burnfield et al., 2004).

Peak plantar pressures were calculated for twenty-one men and eleven women during barefoot and shod walking in a study conducted by Soames (1985). It was observed that there was a change in the behaviour of the gait characteristics under the forefoot area for the participants while shod walking compared to their barefoot walking. The change indicated variations in pressure patterns across the region of metatarsal heads along with increasing the time taken by the toes area under the shod walking condition. It was believed that increasing the peak pressure values during barefoot waking was due to a reduction in area contacted by the plantar surface while barefoot walking compared to walking while wearing shoes (Burnfield et al., 2004). In fact, there was a significant increase in peak pressures and pressure-time integrals registered under the heel and central metatarsal heads areas. This increase was accompanied by a significant reduction in the mean peak pressures under the hallux region for barefoot gait compared to shod walking conditions. In addition, the results demonstrated a reduction in the contact area parameter beneath the plantar surface by 16% for barefoot walking compared to walking while wearing shoes for the older adults selected in the study undertaken by Burnfield et al. (2004). The study suggested that the main underlying bio-mechanical reason for higher peak pressure measures for barefoot walking relative to shod walking conditions was a combination of an increase in the force values and a reduction in the contact area values. For instance, the higher peak pressure values (28%) recorded under the central metatarsal heads were primarily due to an increase of 27% in the peak force variable during barefoot walking compared to shod walking.

Various foot deformities are likely to be caused by inappropriate footwear designs, contributing to the development of forefoot pathology in older people (Frey, 2000; Menz et al., 2005c; Richards, 1991). Consequently, there is a need to develop footwear assessment approaches to manage foot complaints and deformities occurred with advancing age. In a sample of thirty-five older people with forefoot pain to study the influence of adopting different levels of shoe sole hardness, starting from soft, and proceeding to medium and hard on the magnitude of foot loading while the older participants were walking on their preferred normal walking speed on 8-metre walkway. The plantar pressure distribution was measured under the heel, mid-foot, and forefoot regions across the three selected shoe soles using Pedar-X1 measurement systems. The results revealed an increase in plantar pressure values with an increase in the hardness of the shoe sole (Lane et al., 2014).

Foot pain is prevalent among the older female community and has been proven to be strongly associated with wearing shoes. The measurements of the circumference of the instep and the metatarsal heads had larger values for older women with foot pain than those without foot pain according to a research undertaken by de Castro et al. (2010). In terms of these measurements for the men group performed by the same study, the results obtained form that study showed no variations in foot measurements between men with and without foot pain disorder. In an attempt to discover an optimal footwear pad effective for offloading the excessive amount of pressure, particularly beneath the forefoot, different forefoot pads were compared to study their effects on plantar pressure distributed under the forefoot, which is the most painful area for many older adults (Lee et al., 2014a). Thirty-seven older adults with mean age (73.5) years with known forefoot pain were recruited in the study. Plantar pressure measurements at the forefoot region were recorded using Pedar-X systems while the subjects were walking on 8-metre walkway using five conditions of pad arrangement in a standardised shoe, Figure 2.12. The results indicated that forefoot pads were proven to be effective in terms of reducing the pressure distributed at the forefoot region for a number of older people with forefoot pain. The effectiveness of forefoot pads was compared to the results while wearing only a shoe, the control condition. The study suggested that the pads should be positioned with regard to the metatarsal heads region rather than focusing on the pad shape (Lee et al., 2014a).

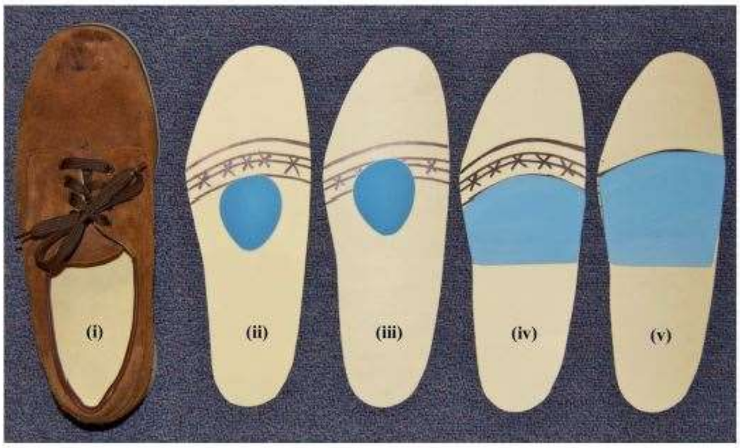

Figure 2.12: The five forefoot pad conditions, i) control-shoe only with no padding, ii) metatarsal dome positioned ten mm proximal to the metatarsal heads, iii) metatarsal dome positioned five mm distal to the metatarsal heads, iv) metatarsal bar, and v) plantar cover, (Lee et al., 2014a).

Footwear design has been identified as one of the factors leading to an increase in the risk of falls because of its implications on body balance control in older community (Connell et al., 1997; McPoil Jr, 1988). The study conducted by Menant et al. (2008) suggested that there is an important need to preference shoes that can be effective enough to prevent prospective falls sustained with advancing age. The authors recommended that based on their research outcomes, shoes with low heel in height and soles with firm slip resistance can enhance balance control, which may decrease the risk of falls for older people. One study suggested that there is an important need for designing specific shoes for older people that can suit their foot morphology and assist them to overcome their foot deformities and any foot pain accompanied by aging. The new elements required for these types of footwear include the provision of proper anatomical fit and a well-fitting toes area, confined heel height, a broad heel type, a firm insole, and effective mechanism for closing along with other safe elements that were suggested through a study undertaken by Jellema et al. (2019).

A number of studies have investigated the influence of different footwear designs on stability and postural control, and with the presence of different lower limb pathologies for older people (Brenton-Rule et al., 2011; Erdemir et al., 2005; Hackney et al., 2010; Sousa et al., 2016; Trombini-Souza et al., 2011). In a sample of twenty patients with neuropathic diabetes with foot deformities of mean age (64.4) years, the influence of adopting the custom-made insoles on the redistribution of plantar loading was studied by Bus et al. (2004). Two types of insoles: standard flat and custom-made were utilised to measure the regional peak pressure and force-time integral values during walking. The patients were at risk of developing ulcers under the first metatarsal bone as reported by a specialist at a diabetic foot clinic. The findings exhibited a significant reduction in peak pressure and force-time integral values under the regions of heel and first metatarsal head while the subjects were wearing custom-made insoles. Furthermore, the peak pressures and force-time integrals were increased under the medial mid-foot area relative to the measurements obtained with flat insoles. Custom-made insoles were shown to be effective in off-loading the area of the first metatarsal head for a number of those patients at risk of ulceration development, compared with the outcomes when using flat insoles (Bus et al., 2004).

In an investigation of the effects of multiple walking surfaces and different shoe features on gait parameters in relation to walking balance and the risk of slips and trips, ten young adults and twenty-six older adults were recruited in the study while wearing a standard Oxford-type shoe during walking on different walkway surfaces: level, irregular, and wet, with different shoe conditions. The results revealed that older people had shown conservative gait patterns while walking on wet and irregular surfaces as discussed through the study conducted by Menant et al. (2009). The findings indicated that elevated heel shoes or shoes with soft soles may impair gait stability for older adults, in particular with walking on wet floors. The results also demonstrated that older people exhibit optimal gait stability while performing the walking on level, uneven, and wet surfaces wearing shoes with a high collar with medium sole hardness (Menant et al., 2009).

Additionally, the prevalence of foot complaints and deformities is common among older people. These deformities can affect the foot shape, leading to variations in anthropometric measurements, which make it difficult for older people to find well-fitting shoes. Therefore, footwear should be designed to suit the alteration in foot morphology for older people (Jellema et al., 2019; Mickle et al., 2010b).

An inappropriate footwear design has been associated with the development of a number of forefoot deformities common in older communities, which in turn can increase the plantar pressures beneath the forefoot area generally, and in particular at the metatarsal heads region (Chang et al., 2014; Klammer et al., 2019; Mickle et al., 2010a; 2011a). Therefore, it is recommended that early clinical interventions and wearing appropriate footwear designs can help older people with foot pains and deformities; as a consequence, the risk of falls can be prevented. According to the above discussion, the present study emphasises the need to design appropriate and well-fitting soles of the shoes based on the research outcomes to cater for the altered pressure patterns observed from the findings in relation to older adults. The soles of the shoes should be designed to be pressure-related relief and available for older adults.

2.10 Walking speed association with altered plantar pressure patterns

Studies have shown that walking speeds affect the distributions of plantar pressure measurements (Burnfield et al., 2004; Chung et al., 2012; Segal et al., 2004). Chung and Wang (2012) investigated the effects of multiple percentages of preferred walking speed, starting from 80% and reaching 140%, for thirty adults of age range between twenty to sixty years. The contact area, peak force, and peak pressure parameters were measured under six plantar regions. Increased walking speed, in particular when the subjects' speed exceeded 120% of their preferred normal speed, resulted in significant increases in peak force and peak pressure measures beneath the heel, medial forefoot, and medial toe areas while the lateral forefoot area exhibited a significant decrease in the peak force values. The reduction in the peak force value under the lateral forefoot region can be explained by increasing the hind-foot eversion accompanied by increasing walking speeds. Increased hind-foot eversion can indicate a pronated foot posture as discussed by Winter et al. (1990). This led to a shift in the loading toward the medial part pf the forefoot region (Chung and Wang, 2012). The findings of the latter study were reinforced by other studies (Burnfield et al., 2004; Segal et al., 2004).

Segal et al. (2004) studied the relationship between different walking speeds and plantar pressures distributed under five foot regions for twenty healthy adults. The subjects were instructed to walk on the treadmill for collection of in-shoe measurements at six walking speeds, starting from 0.75 to 2.00 m/s. From the findings, the heel and hallux regions recorded the highest peak pressure values, which pointed to a linear increase in accordance with faster walking speeds. The peak pressures under medial and central forefoot sections also increased at the initial stage; however, the two regions then had a period with no changes in their values with faster walking speeds. The lateral forefoot region recorded the lowest pressure measures, indicating a decrease in peak pressure with faster walking speeds. The relation of walking speed to the plantar pressure distribution was further explored using the pedobarographic statistical parametric mapping technique while the subjects walking with slow, normal, and fast walking speeds (Pataky et al., 2008). The findings showed similar measurements compared to the traditional subsampling technique broadly used in the research. By comparing the outcomes, both techniques revealed significantly a positive correlation between walking speed and peak plantar pressure measures across the heel and distal forefoot regions; however, the techniques showed relatively inconsistent measurements in relation to other plantar regions.

Plantar pressure distribution is being more thoroughly investigated for both research and clinical fields in order to understand gait pattern variations among various clinical groups, and to evaluate the influence of different footwear designs and surgical interventions (Orlin and McPoil, 2000). It has also been shown that walking speed influences the timing and amount of plantar pressure measurements and this could affect the design requirements of gait study. Therefore, the study performed by Taylor et al. (2004) explored in detail the effect of adopting different walking speeds on the redistribution of plantar pressure measurements for twenty subjects while barefoot walking, using the two-step gait protocol. There was a consistent increase in the maximum force and peak pressure parameters across all selected regions with increased walking speeds except for the lateral mid-foot, first metatarsal, and from the third to the fifth regions of the metatarsal heads. However, there were no significant differences between self-selected normal and slow walking speeds in these two parameters. There was a reduction in force-time integral and pressure-time integral values with increased walking speeds for subjects except for the toes area, which exhibited no changes in timing parameters. The study recommended that different walking speeds can affect both the magnitude and timing gait parameters under most of the plantar regions, as displayed in Figure 2.13.

Furthermore, it has been documented that walking speed has an influence on kinetic, kinematic, spatial, and temporal gait parameters, providing a comprehensive insight in gait analyses for both bio-mechanical and clinical studies with respect to speed-related gait (Schwartz et al., 2008). Nine diabetic patients were recruited and compared with nine healthy subjects to explore whether walking speed could be considered as a feasible measure in association with peak pressure distribution for those patients (Ko et al., 2012). The results pointed out a significant decrease in the steady state walking speed for diabetic patients than those of the age-gender matched cohort. This had directly resulted in a significant reduction of the forefoot to rear-foot peak pressure measures for those patients during barefoot walking as discussed by that study. The results demonstrated that diabetic patients had presented cautious walking characteristics through decreasing their step length and cadence and increasing step time while using barefoot gait. As a consequence, walking speed may be considered as an indicator to identify plantar pressure distribution measurements for diabetic patients during barefoot walking. However, with a more cautious gait, the risk of foot tissue damages and ulcerations can be prevented regardless of other foot deformities that commonly occur in diabetic patients (Ko et al., 2012).

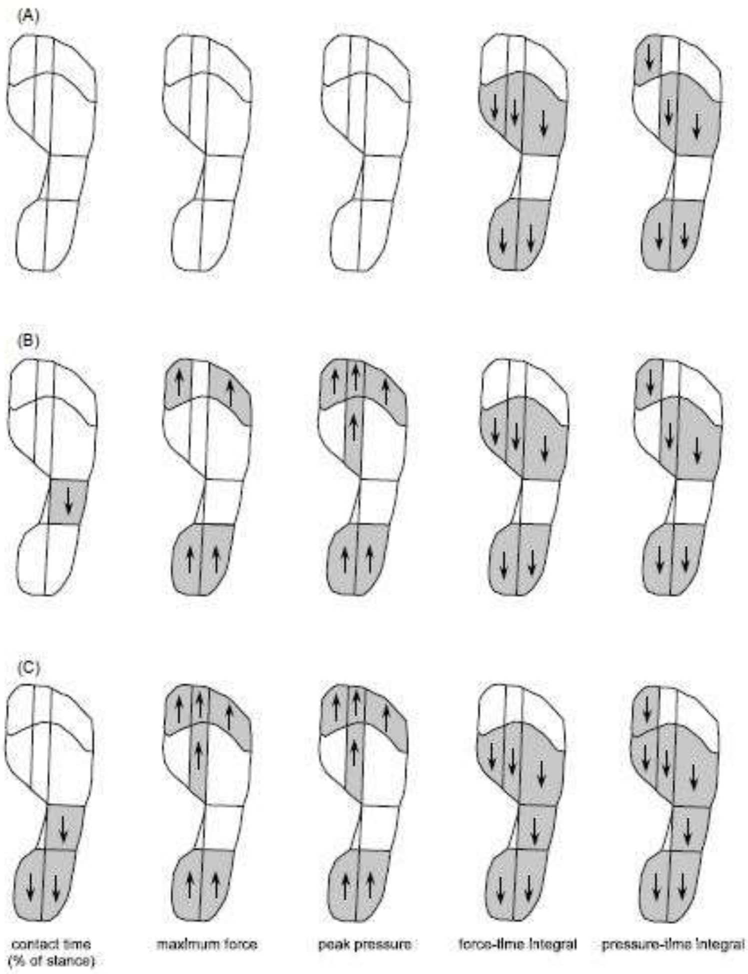

Figure 2.13: The differences in plantar pressure measurements between different self-selected walking speeds: A) slow and normal, B) normal and fast, and C) slow and fast. Shaded areas represented significant variations. The arrows indicated the increase and decrease in the measurements, as depicted by a study (Taylor et al., 2004).

Jogging with treadmills is being increasingly used as a trend for maintaining human body health (Thompson et al., 2003). This form of physical activities is exercised by people from either the gym or even from the home setting. The study conducted by Ho et al. (2010) examined the impact of changes in speed on plantar pressure patterns during jogging on treadmills. Plantar pressure distribution was collected using Pedar-X systems for twenty healthy adults under three different speeds (1.5, 2.0, 2.5 metre/sec). The peak pressures were increased beneath the plantar surface with increasing the treadmill speed. The study provided insights into the bio-mechanics of the foot during joining in association with different speeds.

In a study to investigate whether changes in walking speed influence plantar pressure pattern and the angular motion of the hind-foot area, thirty healthy individuals participated in the collection of plantar pressure measurements using capacitive pressure platform systems. An electro-goniometer device was used to collect the angular motion for subjects' hind-foot area. The findings pointed out that with increasing walking speed, peak pressure values significantly increased at both heel and medial forefoot regions, whereas peak pressure values significantly decreased under the mid-foot and the lateral part of the forefoot area, affecting the medialisation of loading distribution, which may be mediated by increasing the hind-foot eversion as indicated via a study performed by Rosenbaum et al. (1994). The study suggested that walking speeds should be monitored when a comparison of loading patterns of various groups of participants is needed.

Because of the concerns combined with elevated plantar pressures in the development of ulcerations, tissue injuries, and pain common in older people, studies should focus more on plantar pressure patterns investigation among these communities, and have a clear understanding about the factors that can worsen individual conditions. Walking speed has been found to be associated with alterations of loading patterns during gait, indicating higher peak pressure measures with increased walking speeds for elderly people (Deepashini et al., 2014). The study conducted by Burnfield et al. (2004) identified the influence of gait speed on plantar pressure distribution measurements for twenty healthy older adults aged between 55 to 85 years. The subjects were asked to walk on a 10-metre walkway to capture the contact area, pressure, and force parameters in eight plantar regions across three predetermined walking velocities: 57, 80, and 79 m/min. The findings showed that with faster walking, higher peak pressure values were recorded under most of the plantar regions except for the lateral metatarsal and arch regions. This could be due to increased force values under the heel, medial forefoot, and toes areas, suggesting a more pronated foot posture as demonstrated by the studies (Chung and Wang, 2012; Rosenbaum et al., 1994; Segal et al., 2004; Winter et al., 1990).

Apparently, it is crucial to consider the walking speed factor when analysed plantar pressure parameters. In the present work, the contact time of the whole stance phase of the gait cycle was calculated as a basis of subjects' self-selected walking speeds. This can provide a further comprehensive insight into change in the contact time parameter and its association with the redistribution of plantar pressure measurements with advancing age.

2.11 Loaded gait phase for uneven walking surfaces and its association with age-related changes

Human gait analysis has become of particular interest and the subject of many studies in the last few decades in a diverse range of applications including clinical investigation, foot pathologies evaluation, sport, and security identification (Derawi et al., 2010; Di Stasi et al., 2013; Han et al., 2005; Lee et al., 2013a; Muro-De-La-Herran et al., 2014; Sutherland, 2005).

During standing, it has been shown that the ability to balance for older people is maintained by the activities of human ankle muscles as stated by previous research (Huxham et al., 2001; Nashner, 2014; Winter, 1995; Woollacott and Pei-Fang, 1997). However, the activity of human ankle muscles has found to be insufficient to maintain body balance during gait with increasing age, in particular when hazardous events emerged such as slipping and tripping (Winter, 1995; Woollacott and Pei-Fang, 1997). A higher incidence of these events can result in increasing the risk of falls sustained by older people, particularly for those with different foot deformities as indicated through studies conducted by Woollacott and Pei-Fang (1997), and Mickle et al. (2009b). The capability for maintaining the required balance during walking can be influenced by the characteristics of the action or the task being implemented (Carry et al., 1998; Huxham et al., 2001). Hence, it is believed that the challenge of keeping balance control would be greater when walking on uphill and downhill surfaces rather than walking on even surfaces, especially for older people.

The foot complaints with increasing human age have been discussed through a number of studies (Gimunova et al., 2018; Gorter et al., 2000; Keijsers et al., 2013; Leveille et al., 1998; Yokozuka et al., 2019). Older people have been found to have foot problems, specifically the forefoot region involved in most of these cases (Gorter et al., 2000; Keijsers et al., 2013; Yokozuka et al., 2019). These foot problems are associated with: limited human body mobility, increased risk of falling, and a greater chance of developing walking disorders for people from this age stage.

Plantar pressure distribution has been adopted as an evaluation approach of the foot function, foot complaints, and foot deformities occurred with advancing age, which can be useful for both scientific research and clinical settings for the diagnosis of various foot pathologies related to people of an age-matched group (Frykberg et al., 1998; Keijsers et al., 2013; Wallace et al., 2018). For instance, increasing plantar pressure measures under the human foot may potentially lead to the development of plantar tissue damage (Keijsers et al., 2013; Wallace et al., 2018), which can lead to the development of a number of certain foot deformities (Bus et al., 2005b; Caselli et al., 2003; Keijsers et al., 2013; Waldecker, 2002).

Walking on even surfaces has been thoroughly examined across various age groups (Bertsch et al., 2004; Bosch et al., 2009; Burnfield et al., 2004; Kanatli et al., 2008; Machado et al., 2016). Some of these studies have focused on specific pathological conditions (Bacarin et al., 2009; Horisberger et al., 2009; Robinson et al., 2013; Yan et al., 2013; Yu et al., 2011). However, the above studies evaluated the corresponding plantar pressure patterns using a variety of plantar pressure measurements systems (Chevalier et al., 2010; Giacomozzi, 2010; Razak et al., 2012).

A number of previous studies have analysed spatiotemporal gait parameters, and have examined the joint kinetics and kinematics of the locomotor system for young adults while walking on irregular surfaces (Alexander et al., 2016; Franz et al., 2014; Hong et al., 2014; Kimel-Naor et al., 2017; Vieira et al., 2017). Some of these studies have been performed with certain technical requirements (Gottschall et al., 2011; Guo et al., 2006; Item-Glatthorn et al., 2016; McIntosh et al., 2006; Werner et al., 2007). For instance, one of these specific requirements was using a treadmill while collecting the required measurements; however, some technical requirements might lead to an inaccurate reflection of the actual measurements while walking over the ground (Dingwell et al., 2001; Kimel-Naor et al., 2017; Lee et al., 2008) as it has been shown that the walking speed adopted by subjects during gait has an influence on gait parameters (Crowe et al., 1996; Gottschall et al., 2011; Item-Glatthorn et al., 2016; McIntosh et al., 2006; Plotnik et al., 2013). In addition, prior research has been undertaken to analyse joint kinetic and kinematic data for older people while walking on irregular surfaces (Franz et al., 2013; Franz and Kram, 2014; Hong et al., 2015), and to identify the spatial and temporal gait parameters across multiple gait activities (Ferraro et al., 2013; Marigold et al., 2008; Scaglioni-Solano et al., 2015).

Walking on uneven area such as up slopes, down slopes, upstairs, and downstairs has been involved in gait analysis studies for the evaluation of plantar pressure patterns. For instance, dynamic plantar pressure measurements during different ambulatory activities were investigated for patients with diabetic neuropathy (Kästenbauer et al., 1995; Maluf et al., 2004). Their studies assessed plantar pressure patterns during horizontal walking to provide assistance for the clinical evaluation through monitoring the changes in levels of stress between level walking and other functional tasks performed by a group of diabetic patients. The study undertaken by Kästenbauer et al. (1995) aimed to evaluate the potential variations of pressure patterns between level walking with uphill and downhill walking tasks in order to improve the design of insoles for patients with diabetic neuropathy, as this can prevent the risk of developing ulcerations for those patients. Furthermore, the study conducted by Maluf et al. (2004) evaluated the pressure parameters under four plantar regions, including the heel, hallux, and first and third metatarsal heads for diabetic patients at their self-selected speeds during horizontal walking, stair climbing, ramp climbing, and turning as displayed in Figure 2.14. The authors suggested that the outcomes obtained from the study during level walking can be adopted as a standard baseline for the clinical evaluation of pressure parameters for screening stress levels under the plantar regions while diabetic patients perform different activities of their daily life.

In addition, other previous studies have evaluated plantar pressure patterns during horizontal walking on level surfaces relative to stair ascent and descent; however, these studies were examined the loading distribution for young subjects (Kim et al., 2013a; Rao et al., 2012; Wervey et al., 1997). The results obtained from those studies found that plantar pressure distribution measurements were influenced by both the plantar region, and the gait task being performed. A study conducted by Urry (2002) assessed the redistribution of plantar pressure measurements during side slope gait for young adults. The outcomes exhibited a significant alteration in pressure patterns beneath the foot plantar for upslope and downslope positions, pointing out an increase in pressure measurements under the lateral side of the plantar for the upslope position along with an increase at the first metatarsal head area during the downslope position activity.

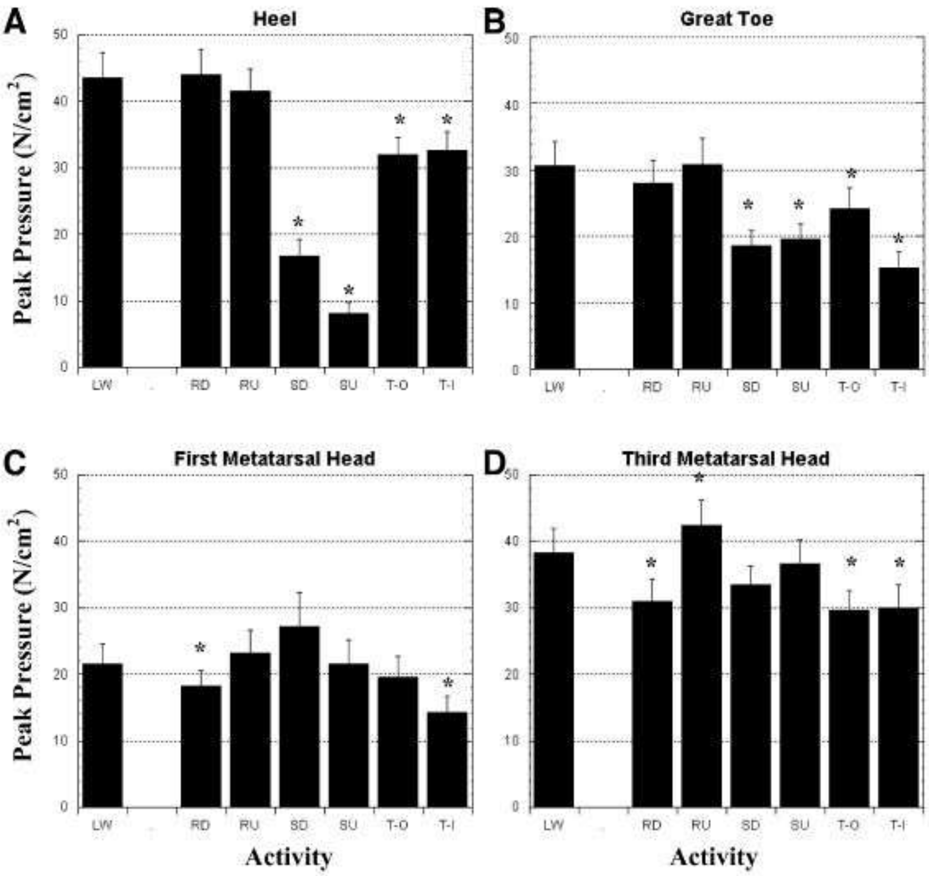

Figure 2.14: Peak pressure measurements under the heel, great toe, and the first and third metatarsal heads during various daily activities, including level walking, descending a ramp, ascending a ramp, descending stairs, ascending stairs, and turning with the foot positioned outside and inside of the turn. * significant differences relative to level walking, adopted from the study conducted by Maluf et al. (2004).

A limited number of studies have explored plantar pressure patterns variations between horizontal walking relative to other walking tasks: uphill and downhill walking steps (Grampp et al., 2000; Ho et al., 2010; Mattar et al., 2015); however, these research tasks were undertaken for young adults, with some specific requirements in their methodology that could limit the outcomes. Grampp et al. (2000) identified plantar loading differences under five gradient conditions: one for horizontal walking, two for uphill, and two for downhill walking tasks. The study adopted a Pedar® in-shoe system as a measurement method to collect the required pressure parameters while the subjects, twenty young adults, walked on the treadmill. With an increasing gradient for the uphill walking task, the results recorded a decrease in peak force and peak pressure measures at the heel area along with an increase in these parameters at the first metatarsal head and the hallux regions compared with level walking outcomes. In contrast, the peak force and peak pressure measures registered higher values at the heel area and lower values at both fourth and fifth metatarsal heads while the treadmill gradient decreased for downhill walking tasks.

Moreover, in a study of a number of healthy female adults, the Pedar-X measurement system was used to examine plantar pressure patterns during treadmill jogging under different speeds and inclined slope conditions. The study adopted two independent protocols. The first was for different speeds on the same slope, while the second protocol was for different inclined slopes at the same speed. The results demonstrated significant changes in plantar pressure distribution measurements beneath the plantar regions selected in the study during treadmill jogging for both protocols. The study provided reference data for female adults in relation to requirements for treadmill jogging activities such as an efficient gradient and speed regardless of the comprehensive insights provided into the bio-mechanics of the foot relating to these daily activities (Ho et al., 2010).

Plantar pressure distribution measurements were determined using a sample of two young female adults during various daily activities. The major daily activities performed in the study were horizontal walking, stair ascent and descent, uphill and downhill walking. The purpose of the study was to form a foundation as a base to attain a standard database for future further research, which can be implemented with a larger sample size. The results exhibited a slight shift in pressure loading towards the forefoot area for the stair ascent status, and a complete pressure shift towards the forefoot region for the stair descent condition relative to outcomes obtained for level walking conditions. A slight modification was detected in plantar pressure patterns under the forefoot region during downhill walking, with no major variations being noticed while the subjects performing the uphill walking conditions (Mattar et al., 2015). However, the study recruited only two subjects, which may lead to an inaccurate reflection of the variations in plantar pressure measurements for various daily activities undertaken in that study.

Prior research emphasised that slope walking has a greater risk than stair walking as indicated by the study conducted by Sheehan et al. (2012). To our knowledge, there is limited information about standard plantar pressure distribution measurements as a comprehensive set for healthy older adults during normal gait within daily activities, including walking on a level surface, and uphill and downhill walking steps. Therefore, the establishment of a reference value of plantar pressure parameters has been suggested, distributed beneath five foot regions, which cover the entire plantar surface. The reference value should be collected while walking on level and inclined surfaces for a group of older individuals wearing pressure sensor insoles. This work and its related methods, results, and discussion will be demonstrated in detail in chapter four.

2.12 Current 3D modelling and lower limb studies

3D models of a human lower limb have become a focus in many studies during the last few years. The 3D models of a human foot can assist clinicians, physiotherapists, and podiatrists in the development of suitable strategies for individuals' treatments for certain physical foot complaints (Petre, 2007). For instance, developing plantar ulcerations for diabetic patients is principally due to abnormal plantar pressure patterns (Mueller et al., 1994; Sage et al., 2001). The abnormal plantar loading for those patients can lead to the development of a number of foot disorders such as prominences in foot bones, stiffness in plantar tissues, and other structural deformities (Cheung et al., 2005; Pitei et al., 1999; Teoh et al., 2020). A number of studies have investigated the effects of surgical interventions and footwear designs to enhance offloading for diabetic patients in order to reduce the elevated plantar pressures and prevent ulcerations (Bus et al., 2008; Bus et al., 2020; Van Netten et al., 2016). Hence, it is important to create an accurate 3D foot model to evaluate the influence of the surgical interventions, various orthotic insoles, and footwear designs (Cheung et al., 2008b; Cheung et al., 2005).

A number of techniques have been adopted for generating 3D foot models, including the use of a flat-bed scanner, Magnetic Resonance Imaging (MRI), Computed Tomography Scan (CT scan), and 3D scanner devices (Cheung et al., 2008a; Gu et al., 2010; Lee et al., 2014b; Martedi et al., 2009; Telfer et al., 2010). Although these methods may be able to generate an accurate 3D models of a static human foot position, they are not suitable for obtaining precise dynamic foot shapes (Antunes et al., 2008; Telfer and Woodburn, 2010).

Additionally, a photogrammetric system comprising multiple cameras for creating 3D models of human foot has been adopted as another technique for the generation of these models. A photogrammetric system utilises the measurements obtained from a number of digital two-dimensional images of the object in order to obtain three-dimensional coordinates of points on the object. Amstutz et al. (2008) adopted a multiple camera-based system for the reconstruction of the 3D foot shape models. The foot shape parameters were defined by the method of principal component analysis. Six cameras were utilised and were placed around the foot in which their corresponding images were used to generate the 3D foot surface model as a cloud of points. The accuracy of the system was ± 2 mm. Chong et al. (2013) presented a video imaging system to generate 3D surface models at various phases of the gait in order to study the changes of plantar features in these phases. The research adopted four camcorders for capturing the video clips necessary for point cloud methods in order to generate 3D plantar surface model. The 3D plantar model was computed with spatial accuracy of 0.3 mm.

The studies have allocated limited space regarding standard guidelines of shoe construction related to the dynamic changes in 3D foot structure (AL-Baghdadi et al., 2013; Krauss et al., 2010). Schmeltzpfenning et al. (2011) discussed the use of photogrammetry techniques to study the dynamic behaviour of the structure of the human foot. The acquired dynamic 3D data of the foot might supply new information assisting in the design of the shoe. However, the authors provided limited information about the plantar shape changes during the main phases of the gait (heel-strike, mid-stance and toe-off). A developed photogrammetric technique utilising twelve video cameras was presented to create the 3D surface models in various phases of gait (AL-Baghdadi et al., 2013; Chong et al., 2013). The acquired shapes of the plantar surface enabled the authors to locate the physical features of the human foot during gait, thus yielding better comprehension of the foot movement in confined spaces. The accuracy of the system regarding the captured 3D surface models was 0.3 mm (AL-Baghdadi et al., 2013).

In photogrammetry, the processing of two-dimensional images can be implemented through a photogrammetric software package, thereby extracting 3D measurements and models of the object. The dense surface modelling (DSM) technique is able to scan image pairs for the purpose of producing dense point clouds and meshed surfaces. AL-Baghdadi et al. (2011) investigated the DSM technique for mapping the 3D surface models of the dorsal and plantar of the foot for the purpose of studying the dynamics of the foot during slow-gait. The authors adopted off-the-shelf HD video cameras to capture the video clips from which the image frames were extracted and then processed. The results of the research showed that the 3D plantar surface model contained less than 0.1 percent of total gaps while the results of 3D dorsal surface model had fewer holes than the generated model of plantar surface, which was approximately 0.02 percent. In either cases, these gaps did not diminish the measurement accuracy of the anthropometric mark positions. The results of the research showed that the overall accuracy of the measurement system was approximately 0.3 mm, Figure 2.15.

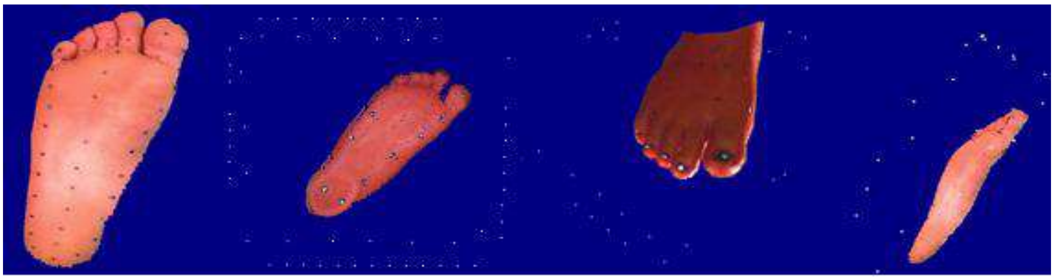

Figure 2.15: Generation of 3D mesh models of a moving foot (Al-Baghdadi et al., 2011).

The development of lower extremity injuries is likely to emerge from the variations in foot posture (Cowan et al., 1993). The relationship between foot posture and lower limb kinematics during walking has been investigated by Buldt et al. (2013). The study conducted by Powell et al. (2011) was performed to investigate the effect of foot posture on peak angle and time to peak angle of the rear-foot and forefoot areas in subjects with high arch and low arch. The research was performed to compare the effect of foot posture on peak angle and total range of motion in normal and pronated foot groups in the areas of rear-foot and medial forefoot (Houck et al., 2008). An investigation of the correlation between changes in the lower limbs and pedal through plantigraphy and photographic capture has been conducted (Cunha et al., 2016). The results produced no strong or moderate correlation between the indices of bruised and angles lower limbs using computerised photogrammetry as a mean of measurements system. The association between foot landing position and the appearance of lower limb deformities has been further studied by Cunha et al. (2018), who showed that plantigraphy and photogrammetry methods were adopted to investigate the relationship between variations in human feet and the corresponding lower limbs in healthy subjects (Cunha et al., 2018). The study emphasised that lower limb angles that were calculated based on computerised photogrammetry techniques were not correlated with footprint indexes.

As was obvious from the above discussion, there are limited trends to study the precise movement of the lower limb using photogrammetric techniques, particularly for the comparison between healthy older adults and adults during gait, specifically during heel-strike, mid-stance, and toe-off phases. This study will focus on the interpretation of innovative data capture techniques regarding the study of precise movement of the lower limb, especially the combination of these measurements with their corresponding plantar pressure data during gait for recruited subjects: older adults and adults. This work will be demonstrated in chapter six.

2.13 Photogrammetric techniques

Photogrammetry is a technique where a number of information for an object can be derived such as the shape, size, and location. The information is obtained from image frames which are sourced from electronic media. The imaging sensor of the electronic media is usually positioned to that specific object at close range (Luhmann et al., 2006). The concept of photogrammetric techniques are based on the central perspective projection model geometry in which it is determined via transformation process, Figure 2.16. In this process, the data is transferred between two spaces from a higher dimensional one to a lower dimensional one (Mikhail et al., 2001; Wolf et al., 2014). The perspective projection is modelled through travelling the light rays from the object to camera pinhole on the image plane (Luhmann, 2010), Figure 2.17.

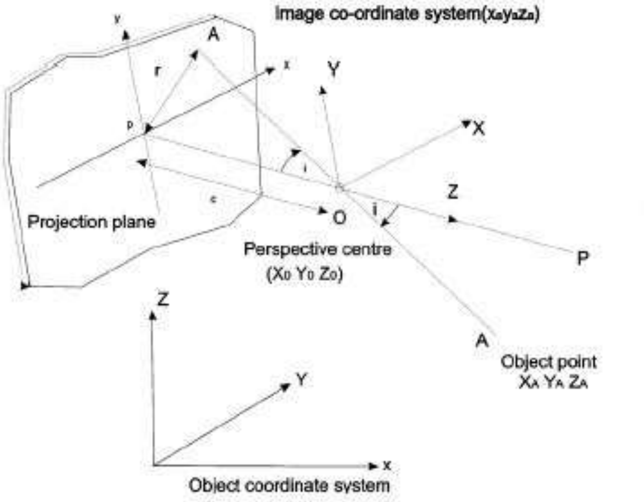

Figure 2.16: The central perspective projection (Luhmann, 2010).

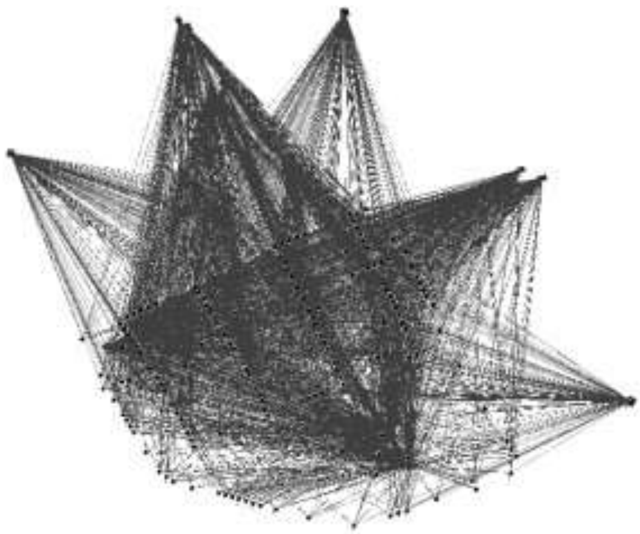

Figure 2.17: Multi-camera 3D configuration of image rays (Luhmann, 2010).

Close range photogrammetric techniques have been involved in a broad way in medical and physiotherapeutic fields (Chong, 2011; Chong et al., 2009; Chong et al., 2008; Majid et al., 2008). These techniques can provide 3D models with high-accuracy, low-cost, and non-invasive measurements for the human foot surfaces. Reconstructing the 3D models of a human foot can be useful for studying the foot performance during gait (Coudert et al., 2006a; Kimura et al., 2011). Recently, a number of studies have utilised photogrammetric techniques to study the dynamic measurements of the human body parts necessary for medical and physiotherapeutic arenas.

In general, there are three photogrammetric techniques for capturing human foot shape during gait. The first photogrammetric approach used for capturing the dynamic shape of human body parts is video camera system. Video camera system was used in recent years for capturing the movement of a human body and for reconstructing 3D models of dynamic parts of a human body, including the face, arm, and the lower limb (Al-Baghdadi et al., 2011; Alshadli et al., 2011; Coudert et al., 2006a; D'Apuzzo, 2002; 2003; Kimura et al., 2011). A proposed anthropometric measurement of photogrammetric system has been presented to determine the change in the top of the foot shape during gait (Coudert et al., 2006b). The authors aimed to evaluate the required parameters for developing footwear which is capable of adjusting its interior size to suit the changes in the foot shape while walking. It was apparent that about 5 mm of the width of the forefoot was increased while the forefoot was on the ground, Figures 2.18, and 2.19.

Furthermore, Kimura et al. (2005) developed an approach to capture 3D measurements of the cross sectional shape of the foot during gait. The authors used a triangulation between a numbers of image frames captured from multi-camera systems. The measurement accuracy was low due to errors in camera calibration process. In an attempt to reduce the error in the measurements addressed in the above study. Kimura et al. (2011) used twelve video cameras for the capture of the dorsal and plantar aspects of the human foot during gait. The aim of the study was to accurately acquire the foot shape measurements through measuring the features of cross-sections of the foot during locomotion, thereby enhancing the design of the shoes. The results showed that ± 0.5 mm as a measurement of accuracy was achieved.

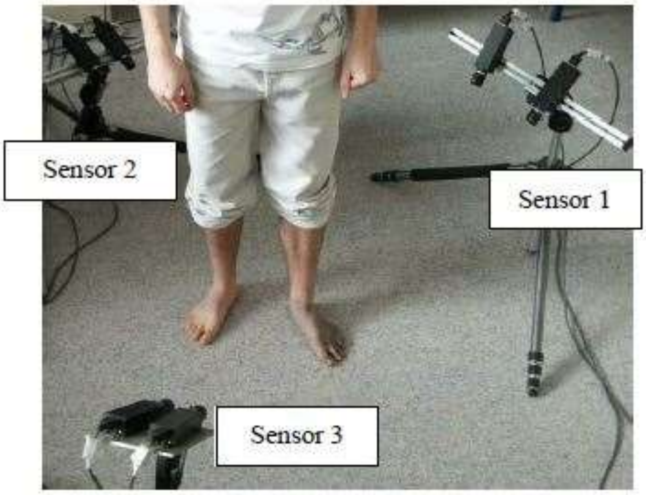

Figure 2.18: Multi-video camera system (Coudert et al., 2006a).

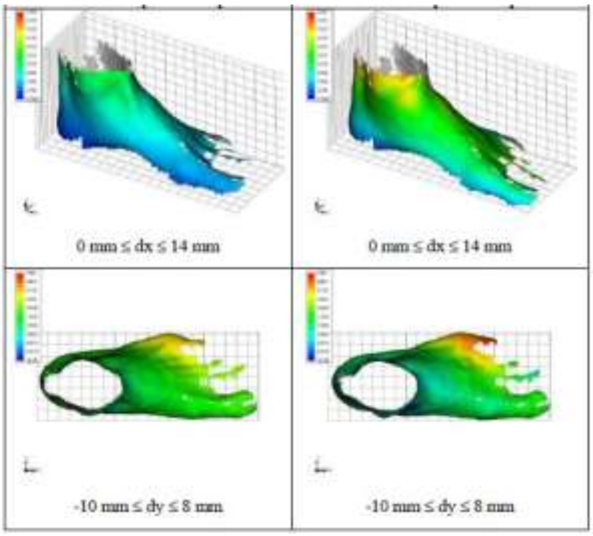

Figure 2.19: 3D surface models of the foot (Coudert et al., 2006a).

In addition, a study was undertaken to determine the change in the foot shape through four cross sectional shapes on the forefoot, instep, navicular, and the heel during standing and walking. The study found that the two cross sections at heel and navicular were more inclined toward a lateral side by 6º during walking compared to the standing condition. Longer medial length and higher dorsal arch were detected during walking than under standing condition. The study also found that the measurement error was significantly higher for breadth measurements and lower for height measurements with values of 1.6 mm and 0.4 mm, respectively (Kouchi et al., 2009). A cross sectional information captured through video camera system was shown to be inappropriate technique for the provision of a complete 3D foot surface models (Yoshida et al., 2012).

Furthermore, three high speed digital cameras were employed to obtain dynamic foot shape measurements during running. The study highlighted the importance of the methodology in reconstructing the foot shape models; however, the 3D model of the dorsum of the foot was not completely achieved (Blenkinsopp et al., 2012). Based on the outcomes of the above studies, video imaging systems were confirmed to be suitable in obtaining dynamic 3D surfaces of the human foot. However, using digital video cameras to capture the motion of the human lower limb has two limitation. The first boundary is that video cameras might not be efficient for monitoring and recording a lower limb movement during fast gait in case the study uses common video cameras. The reason of that is due to a limited number of frames per second that can be captured using common digital video cameras. The second limitation is that a long processing time required to convert the captured video clips to stereo images. These images are essential for deriving 3D models of a human lower limb.

The second photogrammetric approach used for capturing the movement of a human body is camera and projector system. A number of studies have used camera and projector systems for capturing human movement and obtaining dynamic 3D shapes of a human foot (Kimura et al., 2008; Schmeltzpfenning et al., 2011) as these systems can capture the required images with less noise when compared with digital video camera systems. Furthermore, camera and projector systems can be utilised for capturing the movement of a human foot while performing high speed motions such as jogging, and running (Kimura et al., 2008; Schmeltzpfenning et al., 2011).

A system was developed by Kimura et al. (2008) for measuring the 3D foot shape deformation. The study adopted the stereo matching, as a modelling method, between the camera image rays and the projected texture pattern. The study used a camera with high speed recording rate (200 frames per second) and a Liquid Crystal Display LCD projector, shown in Figure 2.20.

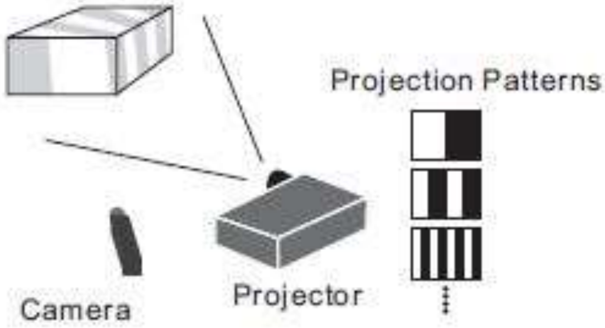

Figure 2.20: The principle of camera and projector systems (Kimura et al., 2008).

The 3D dense surface models of the foot were created with an accuracy of ± 1 mm, Figure 2.21. The accuracy of the system was evaluated based on comparing the obtained 3D foot sole shape to the 3D shape captured through a 3D scanner method (Kimura et al., 2008). However, there was an argument that the developed system is not suitable for deriving 3D model if an object has rough surfaces or when the object has an uneven reflectance properties.

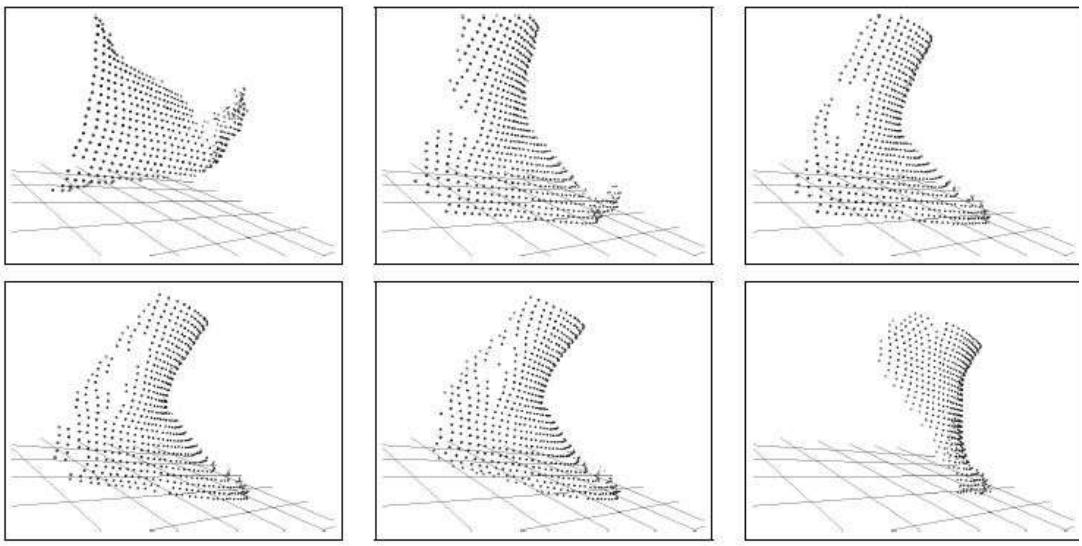

Figure 2.21: The obtained 3D shapes of the tested foot (Kimura et al., 2008).

Furthermore, a study used a dynamic scanner system (DynaScan4D, ViALUX GmbH Company, Germany), which consists of three scanner systems for capturing the foot morphology of a number of male and female subjects. Each scanner included a projector and a high speed camera (Barisch-Fritz et al., 2014; Fritz et al., 2013). The system was mounted on a walkway with long and high of 4.6 m and 0.8 m, respectively. The study used scanner units for capturing the motions of the foot. The first scanner unit was located below the walkway to record the foot morphology from underneath through the glass plate. The other two units were located at the top of the walkway from both sides to capture the foot movements. For system accuracy, the scanner captured a bowl in dynamic condition with binning mode of 4*4 and 0.8 m/s as a station velocity. The measurement error was 0.89 mm (Fritz et al., 2013). However, the 3D shape results of the foot showed incomplete surfaces, particularly during phases of heel-strike and toe-off, Figure 2.22. This means that the camera and projector photogrammetric method is not efficient for obtaining 3D models of a part with rough surfaces or the one with uneven reflectance properties. It is also worth noting that the camera and projector is a high-cost photogrammetric system.

Figure 2.22: Dynamic foot scanning during gait (Fritz et al., 2013).

Furthermore, three cameras and laser projectors were used in a study to provide 3D scans of the foot. The units were synchronised to construct the complete scanning of the foot. The accuracy of the calibrated system was ± 0.5 mm (Jezersek et al., 2011). The study did not use a statistical analysis for system validation. In another recent attempt to measure the dimensions of the human foot, Novak et al. (2014) used the camera and laser projector system. A precision of ± 1.12 mm was achieved for foot height and width. For girth measurements, the system precision was ± 1.73 mm.

A number of studies have adopted the concept of the structured light method for the provision of 3D foot shape information. Schmeltzpfenning et al. (2009) proposed a measurement system of three scanner unites synchronised in a unique way to capture the shape of the plantar foot during walking. The devices were located below the glass walkway platform. At a frame rate of 41 frames per second at normal walking condition, the foot was captured. Static and dynamic foot measurement comparison showed differences in ball width, heel width and arch height of - 4.4, - 4.9 and 5.8 mm, respectively. The above study was further developed by Schmeltzpfenning et al. (2011) for capturing the entire dynamic shape of the foot. Five scanner units, each of camera and projector system, were synchronised to capture dynamic plantar foot shape measurements for 153 subjects. Heel and ball width results showed significant differences during walking. The results indicated a decreasing in instep height and at the ball line of 3.3 mm and 5.6 mm, during walking respectively (Schmeltzpfenning et al., 2011). Figure 2.23, shows the reconstructed 3D shape of the moving foot. However, the study did not investigate the loaded part details of the plantar foot surface.

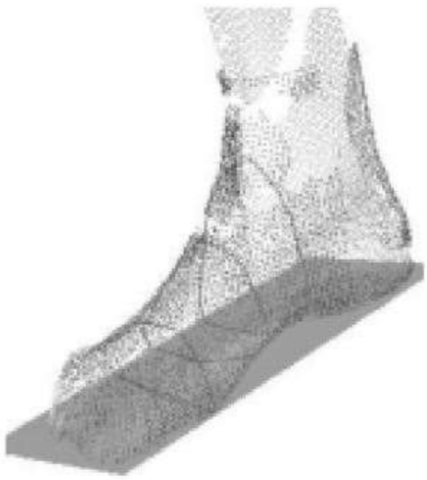

Figure 2.23: The reconstructed 3D shape of the moving foot (Schmeltzpfenning et al., 2011).

In addition, the plantar deformation has been further investigated by Mochimaru and Kouchi (2011) for both walking and running conditions. One camera and one projector unit were used, which were not successful in obtaining a complete 3D foot shape. Moreover, Structured light approach was used in a more recent study for reconstructing the foot plantar surface for 27 subjects in two different days (Thabet et al., 2014). Accuracy and repeatability were studied. The system showed differences in foot reconstruction of 2.8 mm over the two trials. The error computed from the study was ranged between 0.5 mm to 7.0 mm.

The third technique used to capture the motion of the human body is called Time-of-Flight camera system. Time-of-Flight systems have been used recently for civil applications (Oggier et al., 2005). These systems can provide information of 3D images for objects with 50 frames per second (Liu et al., 2011; Oggier et al., 2005; Stürmer et al., 2011a; Sturmer et al., 2008), Figure 2.24. A number of studies have investigated Time-of-Flight systems for monitoring the movements and visualising the 3D surfaces of the human foot during gait (Feng, 2015; Jensen et al., 2009a; b; Liu et al., 2011).

Figure 2.24: Different models of Time-of-Flight cameras (Lefloch et al., 2013).

In a study undertaken by Stürmer et al. (2011b), a Time-of-Flight camera has been used to measure and visualise the dynamic deformation of the human foot during gait. The study used three Time-of-Fight cameras. Two of them were mounted on the left and right sides onto a walkway and one was fixed at the bottom of the platform. The study outcome showed that complete dynamic models of 3D human foot surfaces can be generated with mean angular and translated errors of 0.8º and 0.2 mm, respectively. Foot scanning was investigated by Liu et al. (2011) using Time-of-Flight camera systems. The study used three Time-of-Flight cameras to estimate foot deformation through generated dynamic 3D foot models. Two cameras were located on the top of platform on both sides of the walkway to capture images of the dorsum of the foot, shown in Figure 2.25. The last camera was dedicated to capture foot sole images. A surface model was generated using the poisson surface reconstruction technique developed by Kazhdan et al. (2006), Figure 2.26. In addition, foot deformation was estimated based on the concept of point set registration approach calculated for consecutive images according to study conducted by Myronenko et al. (2010).

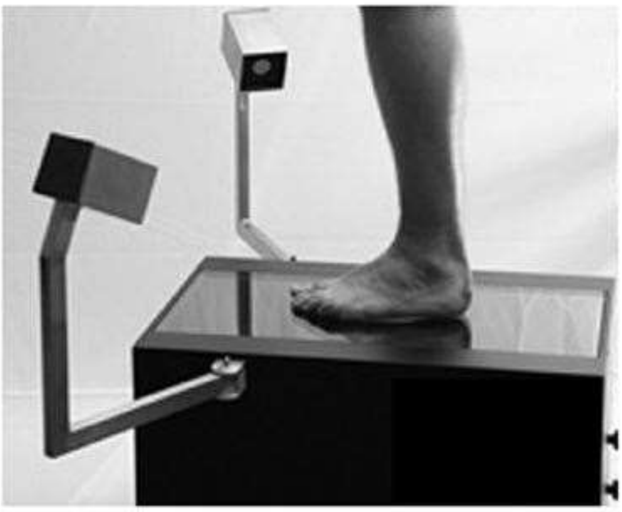

Figure 2.25: Time-of-Flight cameras setup (Liu et al., 2011).

Figure 2.26: Reconstructed foot image frames (Liu et al., 2011).

Furthermore, foot roll-over was evaluated based on dynamic foot scanning through three Time-of-Flight cameras. Intra-class correlation technique revealed a value greater than 0.88 as an intra-subject variability for projected surface and mean height variables computed from foot sole images (Samson et al., 2014).

Time-of-Fight camera has shown its capability of obtaining high accurate 3D data of the foot. It has also been found that Time-of-Flight camera can provide non-invasive dynamic 3D models of a human foot with moderate level in system cost (Liu et al., 2011; Stürmer et al., 2011a; Stürmer et al., 2011b). However, using Time-of-Flight approach can provide images with low resolution. Furthermore, the 3D foot surface models can be generated with noise. In addition, this approach can monitor the human foot during slow gait because it can capture a limited number of frames per second (Feng, 2015; Liu et al., 2011; Oggier et al., 2005; Stürmer et al., 2011a; Stürmer et al., 2011b). It is also worth noting that Time-of-Fight systems has one more major drawback, which is time consumption required to obtain 3D reconstruction as reported by the study undertaken by (Samson et al., 2014).

The above mentioned techniques were proven to be suitable in the provision of dynamic 3D models of a human foot movement. From among these techniques, image-based close range photogrammetry can offer obtaining dynamic surfaces of a human foot with lower level of cost. Video imaging technique using digital video cameras can provide an accurate 3D foot model during gait.

From the above overview based on previous studies, there is lack of knowledge in the investigation of capturing dynamic 3D models of a human lower limb during gait using video imaging technique. Therefore, image-based close range photogrammetric technique will be used in this investigation to capture human lower limb movement during the loading phase of gait, particularly, during the heel-strike, mid-stance, and toe-off phases. This will be demonstrated in chapter six.

Video-based photogrammetric system for digital lower limb feature acquisition was used in the current investigation to provide 3D mapping of human lower limb movement during loading phase of gait. To do so, all video clips should capture the lower limb movement simultaneously. Multiple digital video cameras used to derive 3D models of human lower limbs have to be calibrated using photogrammetric algorithms. Bundle adjustment as a photogrammetric mathematical technique can obtain 3D coordinate points for objects and perform camera calibration process using multiple stereo image frames. Bundle adjustment method was involved in this investigation to calculate the 3D measurements of a human lower limb. This study performed the bundle adjustment method through a software package called

Australis®. The bundle adjustment process is a function found in Australis® software. The bundle adjustment is based mathematically on the collinearity mathematical equations (Luhmann et al., 2006; Wolf et al., 2014).

Optical imaging systems have to be calibrated in order to obtain a number of lens parameters necessary for following imaging processing. Consequently, errors in the processed 3D measurements can be eliminated. The lens parameters include the principle distance, the lens distortion and lens decentring parameters. These parameters are determined through bundle adjustment process. The calibrated focal length, the principal point offset, and lens distortion and decentring parameters are obtained in the following equations known as self-calibration bundle adjustment photogrammetric technique undertaken by previous studies (Chong et al., 2009; Wolf et al., 2014).

$$\Delta m' = \Delta m'_0 - \frac{m'}{PD}\Delta PD + K_1 m'^{r'^2} + K_2 m'^{r'^4} + K_3 m'^{r'^6} + P_1\left(r'^2 + 2m'^2\right) + 2P_2 m'n' - C_1 m' + C_2 n' \qquad (2.1)$$

$$\Delta n' = \Delta n'_0 - \frac{n'}{PD}\Delta PD + K_1 n'^{r'^2} + K_2 n'^{r'^4} + K_3 n'^{r'^6} + 2P_1 m'n' + P_2\left(r'^2 + 2n'^2\right) + C_2 m' \qquad (2.2)$$

Where $\Delta m', \Delta n'$: are axis-related correction magnitudes for errors in imaging process, $\Delta m'_0, \Delta n'_0$: are correction values for perspective centre, ΔPD is correction value for principal distance, K_1, K_2,K_3 are lens distortion parameters, P_1 ,P_2 are lens decentring parameters, and r' is the radial distance. More description for self-calibration bundle adjustment photogrammetric method will be demonstrated in the methodology section provided in chapter six.

2.14 Close range photogrammetry as a 3D spatial measurement method

Close range photogrammetry has been utilised in an extensive way for medical applications since it has been considered as a fundamental tool for capturing high-accuracy spatial data. For instance, the work involves dynamic body parts of the human such as limbs; furthermore, other examples including craniofacial mapping, spine mapping, wound study, and dental study (Chong et al., 2009; Grenness et al., 2008; Majid et al., 2005).

A digital photogrammetry capture technique has been adopted to study the spatial data of the craniofacial area with high accuracy (Majid et al., 2005). The study aimed to establish a national spatial database for a Malaysian craniofacial mapping. The results revealed an accuracy of 0.7 mm in terms of measuring craniofacial distances in laboratory tests. A close-range photogrammetric system with two digital cameras has been used to study detection of the change occurring in the loss in tooth surface in the cervical region of a tooth replica (Grenness et al., 2008). The system generated a digital surface models of a tooth surface without containing a carious cervical lesion. The automatic measurement of mass point of a tooth planar surface was achieved within an accuracy of 4 ± 13 μm in Z direction accompanied with 0.03 mm as a sensitivity of change detection on human mapped tooth annually. A simple digital system of close-range photogrammetry for the purpose of obtaining automatically the 3D spatial coordinates of facial landmark points and for movement tracking of these points as well has been presented by Galantucci et al. (2010). This system assisted researchers to create a 3D computer model which facilitated the process of measurement and tracking of facial movements through automatic procedures. Measuring objects of 50 cm using this system produced 3D coordinates with accuracy of 0.02 mm. A photogrammetric 3D scanning system which can be exploited not only in anthropometry but also for monitoring maxillofacial surgery therapy and for orthodontics has been proposed by Galantucci et al. (2013). Accurate measurements may be accomplished through acquiring, analysing and measuring the characteristics of facial soft tissues. From the measurements of facial soft tissue landmarks, the system has been able to calculate linear measurements, angles, distances and relationships between angles. The measurements extraction by morphometric characteristics of the faces was followed by reconstructing volumetric models of faces for each participant. It was apparent that the system is efficient for facial anthropometry due to its precise measurements. Being able to thoroughly measure soft tissue landmarks, the photogrammetric system assisted the orthodontist and surgeon via presenting the reference standard measures (Galantucci et al., 2013).

A photogrammetric system involving 12 video cameras has been proposed for mapping a cross section of a subject's foot while walking (Kimura et al., 2011). The computed 3D measurements were obtained with approximate accuracy of 1 mm. A six-camera photogrammetric system has been proposed for 3D shape reconstruction of the human foot (Amstutz et al., 2008). An initial 3D foot model which was represented by a cloud of points was constructed from a foot database. The principal component analysis method was used to define the shape parameters. After this, the initial 3D model was adapted to the real foot which it was captured through multiple images. The adaptation was implemented by applying some constraints such as edge points' distance and colour variance. The results showed that the calculated error between the real foot and the reconstructed shape was 1.06 mm.

Furthermore, Chong (2011) adopted a photogrammetric technique involving a low-cost multi-camera imaging system developed to be accessed by health-care practitioners of Charcot-Marie-Tooth (CMT) disease to monitor the progression of the patients' health. The system produced the values of 3D distance difference and standard deviation of 0.323 and 0.052 mm, respectively. It was apparent that the precision of the 3D measurements was 0.4 mm. As a consequence, the system is adequate for medical applications where a demand of 1 mm accuracy is sufficient. Kolahi et al. (2007) proposed a system of two high speed digital video camcorders for determination of joint flexion angles during a gait cycle. The system captured the position of the targets placed on the body of subjects. A distance measurement accuracy of 2.39 mm was achieved from the prototype photogrammetric system. The analysis of results revealed that the computed mean angle from targets on subjects who were martial art experts and non-experts was 87° and 85°, respectively.

The 3D measurement accuracy utilising four-camcorders for close-up human body movement was investigated. Accuracy was shown to be necessary in medical applications. The system was developed to capture the measurements where the object distances were limited between 800 and 1200 mm (Chong, 2012). By mounting a scale bar, in which its 3D distance was known, on a moving human leg, a 0.249 mm was obtained as an average 3D difference between the measured and true distance at an object distance of 800 mm. The results showed that the accuracy of the developed photogrammetric system to measure 3D data for movement tracking purpose was approximately 0.3 mm. Chong et al.(2009) introduced a modified field technique for camera calibration in order to achieve high measurement accuracy in a field environment. The aim of the study was to introduce a custom-built imaging system for studying the human spine in an outdoor environment. Based on the research results, it was apparent that an accurate 3D measurement of anthropometric landmarks of the spine and 3D mapping of the back was obtained.

In general, it has been shown that photogrammetry can be adopted for capturing 3D measurements of the human foot as low cost, high accuracy and non-invasive techniques. However, from the literature, it was observed that there is a limitation in the use of the photogrammetric systems to study the human lower limb movements, in particular for older adults. Therefore, photogrammetric computation techniques will be used in this study to accurately acquire the required measurements of targets positioned on the individual's lower limb. The measurements of human lower limb movement acquired by photogrammetry will be integrated with plantar pressure measurements, especially the centre of pressure trajectories during loading phases of gait. The integrated data will be used to compare the gait characteristics between the two participating groups: older adults and adult individuals.

2.15 Photogrammetry-based geometrical changes visualisation

The complicated shape of the human body in a number of areas, in particular the human craniofacial area, the hand, and the foot requires photogrammetric techniques for 3D mapping and 3D measurement intents (Chong, 2011). A photogrammetric technique developed by Chong et al. (2009) was adopted to measure the changes in spine length and to examine the angular changes in spine shape. In the context of measuring the vector lengths of the spinal segment, the changes in spinal vector length of the samples have been calculated. In addition, the angle changes of spinal segments between landmarks in the sagittal plane for the thoracic, lumbar, and thoracolumbar spine have been calculated for the assigned samples. To clarify, the changes in the shape of the mentioned spine angles were derived from the calculation of 3D coordinates of anthropometric landmarks in a subject's spine. The results proved that the measurement of these landmarks associated with spine vector lengths of spinal segments and the angles between spinal segments were obtained accurately. Kolahi et al. (2007) used two high-speed mini digital video camcorders for determining the angles of subject's joint flexion during a gait cycle. This was accomplished by measuring the position of signalised markers created on subjects' body and limb.

An investigation of the 3D measurement accuracy utilising a photogrammetric system for close-up human body movement was proposed by Chong (2012). In terms of 3D movement tracking using a scale bar mounted on a moving human leg, it was apparent that the use of multi camcorder configuration imaging showed 0.249 mm as the average 3D difference between the measured and true distance at an object distance of 800 mm. Generally, the results of the research showed that a precision of approximately 0.3 mm of the 3D measurements of the developed technique for movement tracking was achieved, which was higher than the desired accuracy required for applications such as medical and physiotherapy.

As was obvious from the above discussion, the main goal of introducing the idea of adopting photogrammetric techniques in the current study is to obtain high accuracy measurements of anthropometric landmarks, which can provide input data for high accuracy 3D models necessary to study the dynamic changes of individuals' lower limb and foot. The next section will point out the photogrammetric system accuracy according to a number of studies undertaken in the last years.

2.16 Photogrammetry-based 3D imaging and system evaluation

The configuration of the photogrammetric system has to be set up in an optimal way, thereby achieving an accurate individual gait recording via multi video camera system. This in turn can ensure acquiring the required 3D measurements. The multi camera system should be configured in a way which allows it to capture convergent photography of the whole individual's lower limb and foot simultaneously (Chong et al., 2009). It is also essential that every desired target on an individual's lower limb and foot should be in the field-of-view of at least three cameras. In terms of finding the sufficient number of cameras in the optimal configuration of the research to achieve a sufficient coverage with highest accuracy, several studies adopting a varied number of cameras to generate a 3D model using photogrammetric systems. Kimura et al. (2011) proposed a 12 video camera system to capture images of the foot during walking. A 3D measurement accuracy of about 0.5 mm was achieved from the research results. Chong (2012) exploited four HD video camcorders for investigating the 3D measurement accuracy of human body movement for medical applications. The research showed that the precision of the 3D measurements was roughly 0.3 mm.

Researchers have emphasised that a close range photogrammetric system plays an intrinsic role in terms of capturing high-accuracy spatial data, particularly in studying dynamic human body parts, such as limbs (Chong et al., 2009). The authors of this study have proposed photogrammetric techniques for measuring human body dimensions. The objective of the research was to measure the changes in spine length and to examine the angular changes in spine shape. The results showed that the measurement of the proposed photogrammetric technique had the capability to detect the height and shape changes of the spines to a mean accuracy of 0.74 mm. By measuring the mean and the standard deviation of the assigned samples, the research results revealed that an accurate and reliable anthropometric landmark measurement of spine vector lengths of the spinal segments and the angles between the spinal segments was achieved.

A low-cost multi-camera imaging photogrammetric system was developed to be accessed by health-care practitioners of the Charcot-Marie-Tooth (CMT) disease application to monitor the progression of the patient’s health (Chong, 2011). The photogrammetric system adopted for CMT disease investigation produced a mean 3D distance difference of 0.323 mm and a corresponding standard deviation of 0.052 mm which ensured the sub-millimetre precision that exceeded the desired accuracy of 1 mm essential for medical applications. Chong (2012) presented a photogrammetric system which aimed to investigate the 3D measurement accuracy utilising multi-HD camcorders for close-up human body movement video imaging necessary in medical applications where the object distances were limited to between 800 and 1200 mm. The static 3D measurement results (the mean 3D distance difference and the standard deviation) were shown using images captured by individual camcorders. The system results showed that a 3D measurement accuracy of under one-tenth of a millimetre was obtained by these camcorders.

Based on recent research outcomes in terms of evaluating a photogrammetric system spatial accuracy, the system can be used efficiently in the current research due to its anticipated capability to study the dynamic changes of human lower limb and foot during gait with high accuracy.

2.17 3D surface model of human lower limb and foot movement with plantar pressure data synchronisation

Generally, for this study, it is required to synchronise the data of the 3D model with the plantar pressure data to correlate the data analysed from plantar pressure software at the same time with data of a 3D lower limb and foot model created by photogrammetric techniques, thus acquiring significant parameters at a specified time. An investigation of the centre of pressure under the foot while walking was conducted by measuring the forces under the foot during gait integrated simultaneously by filming the plantar surface (Grundy et al., 1975). By using a computer program, the plot curves of centres of pressure and the force resultant from the force-plate were calculated. The research used a synchronising clock as a means of correlation between the data obtained from the force-plate and the cine film of the contact areas of the subject's foot. The clock appeared on the cine film and produced a simultaneous signal with the data captured by the force-plate.

Chong et al. (2014) conducted research which aimed to match the dynamic 3D model, captured by photogrammetric techniques, with the plantar ground reaction force and the plantar pressure data, computed during the loading phases of gait. Twelve video cameras were utilised to capture the images of the foot. By using multiple video cameras and the requirement to synchronise the captured video clips, a laser-guided device was built and installed on the walking stage which activated a red-flash LED as shown in Figure 2.27. The time of activation the red flash of the LED coordinated with the individual hitting the force plate or the pressure mat, thus the video cameras were synchronised through tagging the frames that were recorded in multiple video clips.

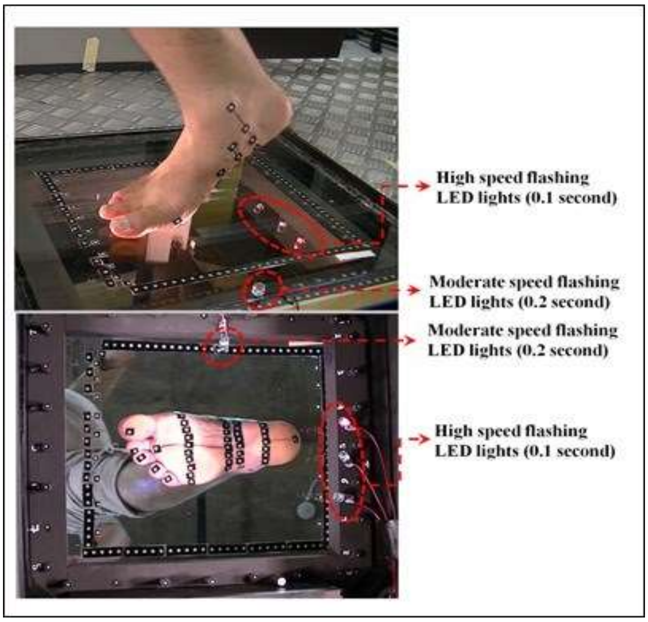

Figure 2.27: The timing LED (Chong et al., 2014).

The synchronisation of the force plate or pressure mat recording with the video recording was accomplished by sending a signal from the laser synchronising device to the force plate or pressure mat and setting off the LED attached near the sensing area at the time of blocking the laser beam by the ankle during the gait. The finding of that research revealed a high percentage of correlation between the two obtained data.

Hence, it is crucial to include a synchronisation electronic device in the current research due to the necessity of performing the correlation between the data of 3D model of the lower limb and foot captured by the multi-video camera system and the data recorded by the plantar pressure system. Being able to attain a number of parameters at various phases during gait, the research aim can be fulfilled by performing a comparison of these parameters in terms of their values for older adults and adults. A component of the present investigation focuses on evaluating the integration of the 3D lower limb measurements with the corresponding plantar pressure data while the subjects were barefoot on their self-selected speed during loading phases of gait for the two groups participating: older adults, and adults. This is clarified in chapter six.

2.18 Identified research gaps and the conclusion

This review provided a discussion of plantar loading distribution measurements, particularly for older people with different foot disorders. However, relatively few studies have explored the plantar pressure patterns to investigate the gait characteristics during loading phases of gait for healthy older adults, and the differences of their normal gait with that of adult subjects. Hence, a gap was identified where standard values of pressure parameters measured during normal walking at self-selected speed for healthy older adult individuals have not been established, in particular the comparisons of these measurements with the corresponding outcomes from adult individuals using F-scan sensors as a measurement system. This can assist in identifying the most significant changes under the plantar surface that are likely to be modified with increasing human age.

Furthermore, a review of the gait loading patterns during walking on uneven surfaces was provided in this chapter. Although few studies in the literature evaluated plantar pressure distribution under various walking activities, to our knowledge there were no studies to investigate plantar pressure patterns for a number of healthy older adult individuals. Therefore, the purpose of this thesis is to fill the research gap by providing a better understanding of the variations in gait patterns between walking on level surfaces, with uphill and downhill walking steps activities performed by a number of older adults wearing pressure sensor insoles.

Additionally, this review has shown that a number of conventional techniques can be adopted for obtaining 3D measurements of the human lower limbs especially for static foot shapes. Based on the outlined literature, image-based close range photogrammetry outweighs the other techniques in terms of the provision of a realistic representation of the dynamic assessment of the human lower limb and foot during gait regardless of other advantages provided by these systems such as low cost, high accuracy, and non-invasive methods of capturing human gait tests. The close range photogrammetry technique was developed in the present thesis to study the foot rotation and loading for older adults, compared to adults. This aim was accomplished through integrating the 3D measurements of lower limb movements captured by photogrammetric techniques with the corresponding plantar pressure data captured using Tekscan Matscan systems for selected barefooted subjects of the two cohorts: older adults and adults. Hence, a component of this investigation identifies the lower limb movement during gait and its relation to the centre of pressure trajectory during the main phases: heel-strike, mid-stance, and toe-off of the stance phase of the gait cycle using a developed technique based on the correlation between both obtained data. The next chapter investigates the loaded gait phase comparison between older adults and adults in five anatomically defined foot regions during the whole stance phase of the gait cycle.

CHAPTER THREE

LOADED GAIT PHASE OF UN-NORMALISED AND NORMALISED COMPARISON BETWEEN OLDER ADULTS AGED 65-80 YEARS AND ADULTS AGED 25-45 YEARS

3.1 Introduction

The study was designed to examine the variations of dynamic plantar pressure between older adults and adults. The purpose of the present study was to highlight the gait patterns of normal walking for the older adults' group by comparing them to the adult subjects' group in five anatomically defined plantar regions during the whole stance phase of the gait cycle to thoroughly understand the causes of the development of foot conditions. This information should be useful to use as a reference value to compare it with various gait pathologies sustained with advancing age. Furthermore, the second purpose of the study was to evaluate plantar pressure parameters based on the average weight for each specific group and observe whether the normalised data had implications on plantar pressure distribution comparison for the two selected cohorts. Forty subjects were recruited in the study to perform gait trials at their self-selected speed using an insole pressure sensor system. The results showed higher plantar pressure measurements for the older adults' group underneath a number of selected plantar regions, except the mid-foot area, which exhibited lower plantar pressure values when compared to the adult subjects. In addition, measured and analysed normalised plantar pressure parameters, taking into account the percentage of the averaged weight for each group, revealed similar results to those undertaken to the initial measured data, except for a small number of variations. This study could be intrinsic to not only scientific research, but also to clinical aspects for assessment and also to the treatment of a diverse range of foot problems that predominantly occur during gait; hence, the study could help to avoid a number of foot complaints that may develop with advancing age.

3.2 Background

Foot complaints associated with age-related changes can have a major influence on human mobility as the foot constitutes the vital animated part, connecting the human body, while standing and walking, with the ground (Keijsers et al., 2013; Menz, 2015; 2016; Rodgers, 1995). With advancing age, foot complaints are associated with, an increased risk of falling, impacting mobility, limiting balance while walking, and increasing the development of gait disorders (Abouaesha et al., 2001; Armstrong et al., 1998; Keijsers et al., 2013). It is important to study the dynamic behaviour of normal foot function, which can assist in understanding age-related gait variability (Callisaya et al., 2010), to compare it with foot problems in patients for treatment purposes (Kimmeskamp et al., 2001; Rodgers, 1995). Measuring dynamic pressure distribution can identify the anatomical foot deformities encountered by those patients (Hessert et al., 2005; Rodgers, 1995; Tanaka et al., 1996). These deformities can contribute to impairment of balance and deterioration of functional ability in older people (Menz et al., 2005b).

A number of studies have compared the plantar pressure parameters between groups of older subjects with and without a specific foot condition. In one study, peak pressure and pressure-time integral values were calculated in a number of community-dwelling older people, both men and women, aged over sixty years with toe deformities. Plantar pressure distribution was assessed for barefoot walking by an Emed-AT4 pressure plate system. An alteration of plantar pressure patterns was found under the forefoot region when compared to the control group, leading to variation of weight distribution beneath the foot during gait (Mickle et al., 2011). Hallux valgus is one of the most common toe deformities and is associated with increased risk of falling faced by elderly people (Menz et al., 2006b; Mickle et al., 2009; Nix et al., 2013). Furthermore, a study undertaken by Zammit et al. (2008) evaluated the variations in plantar pressure distribution during barefoot walking for older subjects with and without osteoarthritis of the first metatarsophalangeal joint. It was found that older people with this foot condition had higher maximum force and peak pressure values under the regions of the hallux and lesser toes when compared to the control group: older adults without foot conditions. Additionally, a number of Parkinson patients were involved in a study conducted by Kimmeskamp and Hennig (2001) to analyse their plantar pressure characteristics during walking. The results showed significant differences in the plantar pressure parameters under selected plantar regions between those patients with the control group. The change in gait characteristics for patients with this condition was believed to be owing to a mechanism adapted by the patients to eliminate their unsteadiness while walking.

Changes in the structure, biomechanics, and function of the human foot occur with advancing age (Burnfield et al., 2004; Callisaya et al., 2010; Hessert et al., 2005; Rodgers, 1995; Rodríguez-Sanz et al., 2018). It is vital to maintain efficiency and safety for older adults walking ability, which can limit the risk of falling and help to maintain independence (Callisaya et al., 2010). A number of studies have investigated the variations of dynamic plantar pressure distribution between young with older and elderly people using a variety of systems. Plantar pressures were compared for thirty-five young adults aged 18-24 years, and thirty-five elderly subjects aged 71-90 years using a capacitive platform system. Pressure distribution for barefoot walking was assessed under seven plantar regions. It was found that the region under the first metatarsal head yielded higher peak pressures for elderly subjects than those of young adults, whereas the elderly subjects recorded lower peak pressure measures under the mid-foot region than the young adults (Kernozek et al., 1995). In a sample of nine young and six elderly subjects using shoe insoles of 99 capacitive sensors each, foot pressure distribution was calculated at their normal walking speed on the treadmill. Mean forces and pressures were measured under nine foot regions. The findings showed that elderly subjects had more weight bearing on their plantar lateral side than young subjects, affecting the balance and limiting the walking ability for elderly people (Hessert et al., 2005). Furthermore, twenty adults, aged 55-85 years were involved in a study to identify the impact of walking velocity and footwear conditions in eight foot regions on the plantar pressure variables. The results pointed out that higher plantar pressure values for selected subjects were associated with barefoot and faster walking conditions (Burnfield et al., 2004).

The F-scan sensors have been identified as a cost-effective, efficient and reliable system for plantar pressure measurements (Ahroni et al., 1998; Hida et al., 2017; Mueller et al., 1996; Razak et al., 2012). The in-shoe F-scan sensor is flexible as it is portable, allowing a broad variety of research to be performed, including various gait tasks and multiple footwear designs. These sensors are embedded in the subject’s shoes; hence, they will eventually reflect the plantar pressure measurements based on the interface between the plantar foot and the shoes (Razak et al., 2012). The F-scan sensors have been adopted in our research to identify the range of plantar pressure values distributed in healthy older adults and adult subjects.

As gait impairment and maintaining the balance during loading phases of gait can be considered as significant concerns related to advancing age (Lord et al., 2007; Menant et al., 2008; Rubenstein, 2006; Sturnieks et al., 2008), relatively few studies have investigated gait for healthy older adults, and the variation of their normal walking with the corresponding adults' group using F-scan sensors, thereby bringing comprehensive insights into plantar pressure distribution differences, in the two cohorts. Therefore, the purpose of this research was to evaluate plantar pressure measurement differences between adult subjects and the older adults, prior to reaching an elderly stage and deteriorating in terms of maintaining healthier foot plantar. This could possibly be achieved by trying to discover an appropriate insole pad that could be designed based on the outcomes achieved from this study, or design assorted interventions to support balanced pressure distribution. Consequently, a number of developed foot complaints sustained with advancing age, in particular while performing weight bearing tasks, can be prevented, which in turn can enhance the plantar pressure distribution patterns. Additionally, a range of pressure parameters measured under normal walking at self-selected speed condition using F-scan sensor systems collected for older adult subjects could be used to form a reference value to be compared when investigating different pathological cases in clinical domains faced by older people, having an age similar to that of the group being selected and studied in this research.

The second purpose was to normalise the plantar pressure parameters based on the average weight for each group as the older adults' group might have a higher average weight, compared to the adults' group to enable more meaningful comparison. This objective was to explore whether adopting the normalisation would change the differences measured and analysed for the initial set of plantar parameters between the two groups participating in our study: older adults and adult subjects.

3.3 Methods

3.3.1 Participants

Forty subjects were recruited in this study: twenty older adults aged 65-80 years (mean age 72.3 ± 5.16 years, weight 82.25 ± 9.34 kg, height 173.55 ± 8.72 cm, and BMI 27.44 ± 3.76 kg/m^2), and twenty adults aged 25-45 years (mean age 33.25 ± 7.01 years, weight 72.2 ± 16.48 kg, height 167.8 ± 7.59 cm, and BMI 25.4 ± 4.22 kg/m^2). The subjects had no pain associated with the foot and lower-limb during normal walking, and no known foot conditions, which might affect their gait. Table 3.1 shows the demographic properties for all forty individuals participating in the study along with the mean and standard deviation ranges for these demographic properties of both groups shown in Table 3.2. The mean contact time of the entire stance phase for both cohorts: older adults and adults was (0.71 ± 0.08, 0.64 ± 0.05 sec), respectively. The participation of the human subjects in this research was conducted under an approved ethical clearance application form (H18REA160) obtained from University of Southern Queensland Ethics Committee.

Table 3.1: Demographic properties for forty individuals, showing the age in (years), weight in (kg), height in (cm), body mass index (BMI) in (kg/m^2), and contact time in (sec).

	Age	**Weight**	**Height**	**BMI**	**Shoes Size**	**Gender**	**Age Stage**	**Contact time**
Subject 1	73	67	171	22.91	9	Male	Older Adult	0.66
Subject 2	74	71	173	23.72	9	Male	Older Adult	0.67
Subject 3	65	77	163	28.98	9	Female	Older Adult	0.69
Subject 4	69	64	164	23.80	8	Female	Older Adult	0.54
Subject 5	80	75	180	23.15	11	Male	Older Adult	0.69
Subject 6	78	78	182	23.55	11	Male	Older Adult	0.66
Subject 7	80	87	183	25.98	10	Male	Older Adult	0.79
Subject 8	78	91	180	28.09	10	Male	Older Adult	0.74
Subject 9	65	91	168	32.24	9	Male	Older Adult	0.63
Subject 10	66	94	170	32.53	9	Male	Older Adult	0.80
Subject 11	67	80	178	25.25	9	Male	Older Adult	0.74
Subject 12	68	83	180	25.62	9	Male	Older Adult	0.77
Subject 13	78	76	181	23.20	9	Male	Older Adult	0.73
Subject 14	76	79	179	24.66	9	Male	Older Adult	0.89
Subject 15	75	90	175	29.39	8	Male	Older Adult	0.66
Subject 16	74	92	177	29.37	8	Male	Older Adult	0.74
Subject 17	73	80	150	35.56	8	Female	Older Adult	0.82
Subject 18	70	93	178	29.35	9	Male	Older Adult	0.68
Subject 19	72	97	179	30.27	9	Male	Older Adult	0.68
Subject 20	65	80	160	31.25	9	Female	Older Adult	0.60
Subject 21	32	57	162	21.72	8	Male	Adult	0.61
Subject 22	44	73	164	27.14	8	Male	Adult	0.60
Subject 23	32	85	165	31.22	8	Male	Adult	0.71
Subject 24	39	81	173	27.06	9	Male	Adult	0.72
Subject 25	30	73	176	23.57	9	Male	Adult	0.64
Subject 26	27	95	180	29.32	9	Male	Adult	0.68
Subject 27	38	96	173	32.08	9	Male	Adult	0.76
Subject 28	45	84	176	27.12	9	Male	Adult	0.74
Subject 29	43	87	169	30.46	9	Male	Adult	0.62
Subject 30	43	103	186	29.77	10	Male	Adult	0.64
Subject 31	26	58	164	21.56	8	Female	Adult	0.64
Subject 32	25	66	166	23.95	8	Female	Adult	0.65
Subject 33	29	51	166	18.51	7	Female	Adult	0.63
Subject 34	28	66	163	24.84	7	Female	Adult	0.64
Subject 35	27	53	164	19.71	6	Female	Adult	0.57
Subject 36	26	60	156	24.65	7	Female	Adult	0.58
Subject 37	25	62	158	24.84	8	Female	Adult	0.61
Subject 38	30	50	160	19.53	8	Female	Adult	0.56
Subject 39	38	87	170	30.10	10	Female	Adult	0.63
Subject 40	38	57	165	20.94	9	Female	Adult	0.62

Table 3.2: Mean values and standard deviations for demographic properties with the P-value < 0.05 demonstrating a statistical difference between the two groups: 20 healthy older adults and 20 healthy adults.

	Age	Weight	Height	BMI	Contact time
Older Adults	72.3 ± 5.2	82.3 ± 9.3	173.6 ± 8.7	27.4 ± 3.8	0.71 ± 0.08
Adults	33.3 ± 7	72.2 ± 16.5	167.8 ± 7.6	25.4 ± 4.2	0.64 ± 0.05
P-value	5.5466e-10	0.0232	0.0232	0.2753	7.2529e-04

3.3.2 Equipment and protocol

The study adopted an in-shoe 3000E F-scan® pressure sensor (Tekscan, Boston, MA) system sampling at 100 Hz for capturing plantar parameters, namely contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral. An informed consent form was signed by the participants who took part in this research to show their agreement to participate. Demographic properties, such as age, weight, height, and gender were obtained from subjects of both groups. The collection of the plantar pressure parameters was self-captured for the two participating groups: older adults and adult subjects.

Subjects were provided with standard shoes of different sizes. Each subject was asked to wear an appropriate size from these shoes with an inserted in-shoe 3000E F-scan® sensor, Figure 3.1. In-shoe pressure insoles can provide a visualisation of the temporal characteristics under the plantar surface while undertaking weight bearing tasks (Spooner et al., 2010). Additionally, using pressure insoles permits the measurement of the plantar parameters of the human foot during various functional and environmental activities (Mueller and Strube, 1996). Pressure insoles can assist in the provision of plantar pressure distribution beneath the entire foot plantar with high reliability (Kernozek et al., 1996; Putti et al., 2007), and observe a number of plantar lengths and the existence of a number of toe deformities (Morag et al., 1999). Providing this information can be beneficial in pathological diagnosis (Orlin et al., 2000). The F-scan pressure sensor insole includes 960 sensing cells and can provide high accuracy measurements due to its effective spatial resolution (Hsiao et al., 2002) of four sensors per cm^2 (Chevalier et al., 2010; Kim et al., 2013), allowing maximum pressure measurements of 517 kpa for each sensor (Hida et al., 2017). The F-scan sensor is undetectable inside the shoes because of its thinness so it does not interfere with the individual's normal gait. Hence, with the above mentioned, it was suggested to adopt these sensors in the current study, particularly when older people are the main study participants, thereby reflecting reliable gait patterns for this age group. The sensor sheet was precisely taped with the shoe sole so there is no possibility for the sensors to slip while performing the gait, enabling the achievement of a reliable measurement (Razak et al., 2012). The insole pressure system was calibrated before the gait test for each subject in advance based on manufacturer's guidelines.

The demonstration for the research procedures was explained to the subjects prior to the commencement of the gait test. Furthermore, in order to be familiar with the required procedures, the subjects were given few minutes to practise the gait tests, Figure 3.2. A standard gait was required to be carried out by subjects represented by the standing position at the commencement, followed by proceeding forward along a 10-metres walkway at their self-selected gait speed, repeating the same gait test for each participant for the following week for measurement purposes and for the reliability of subject's tests. These sessions were conducted at the University of Southern Queensland laboratory. In this study, for each session, it was suggested to compute the mean of the plantar pressure parameters of the three middle stable steps of human gait, instead of computing and analysing the average data for all ten recorded gait steps performed by the subjects to avoid abnormal gait patterns accompanied by the initiation and the termination; hence, higher accurate results could be obtained (Fuchioka et al., 2015). The plantar parameters beneath the foot were measured and computed using FSCAN Research, version 6.7 software for a number of plantar regions, namely the whole foot, heel, mid-foot, forefoot, and the hallux to study the variations of foot loading patterns for the whole stance phase of the gait cycle, started from 0 % and completed within about 60 – 62 % of the full gait cycle (Burnfield, 2010) between the two selected cohorts. Figure 3.3 shows the five regions adopted in this investigation. Figure 3.4 shows the data collection procedure used to capture the required data for selected subjects from both group in this study.

Figure 3.1: An in-shoe 3000E F-scan® sensor of F-scan® pressure (Tekscan, Boston, MA) system.

Figure 3.2: An older subject wearing in-shoe 3000E F-scan® sensors.

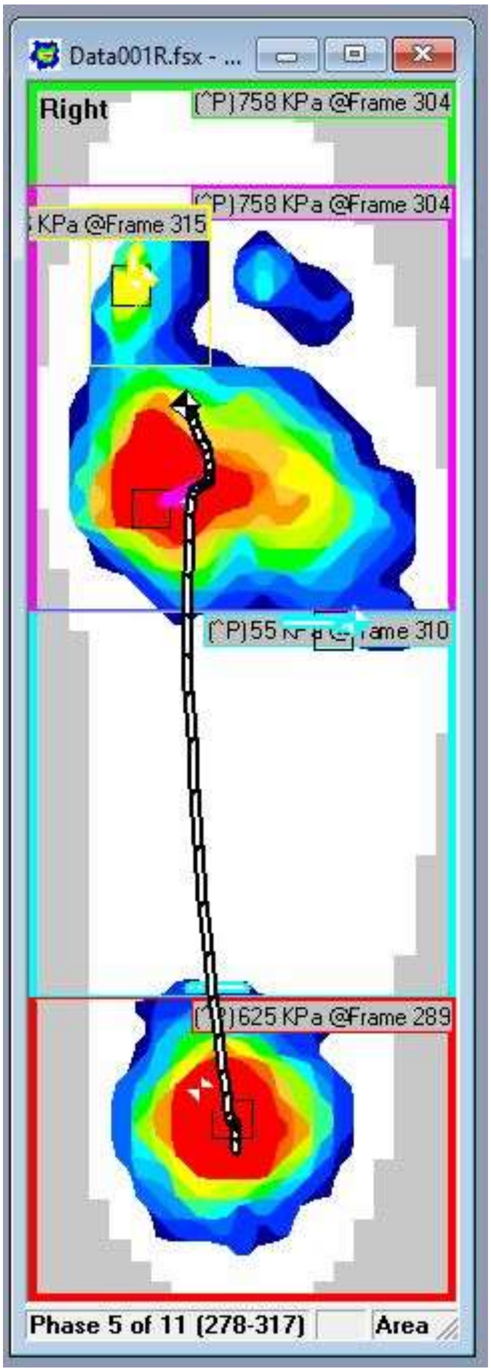

Figure 3.3: Plantar pedobarographic image for older adult subject showing five selected plantar regions.

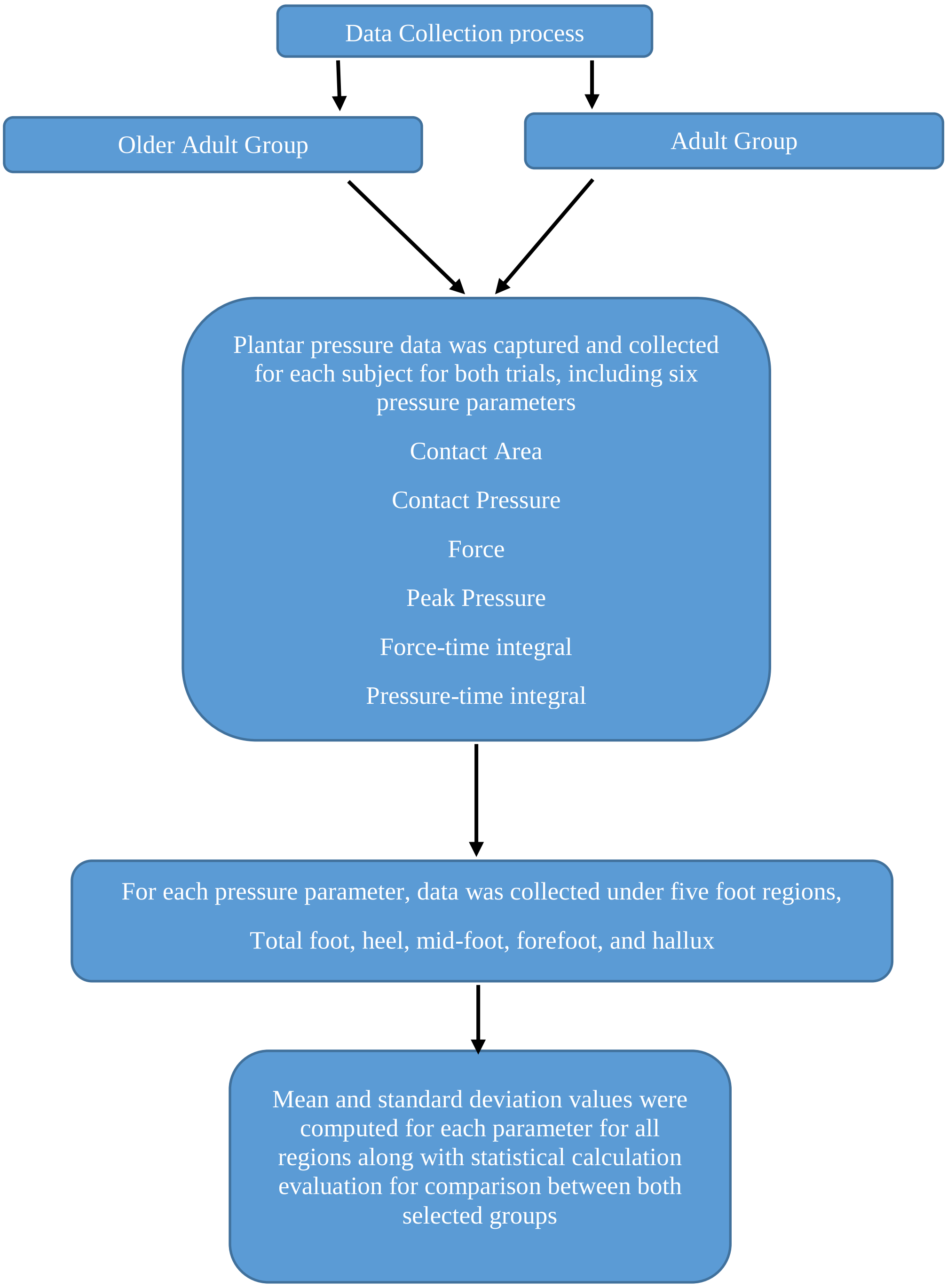

Figure 3.4: Data collection procedure used in the study for loaded gait phase comparison between older adult and adult groups**.**

3.4 Statistical evaluation

Intraclass correlation coefficients (ICC) were adopted to assess reliability for the two repeated sessions; each session comprised the mean of the three middle steps of gait protocol, for regional plantar pressure parameters. Average measures were calculated for each group separately. An ICC of 0.971 indicated excellent correlation within the older adults' group along with an average measure ICC of 0.985 for the adults' group, showing an excellent correlation preferably to be subsisted in clinical scopes (Bautmans et al., 2011; Streiner et al., 2015). A value of 0.954 was obtained for system validity using Pearson correlation. The correlation was significant at the 0.01 level (2-tailed). IBM SPSS Statistics version 25 has been utilised to perform ICC tests and Pearson correlation test for system validity.

The variations of plantar pressure patterns between the two groups participated in the study -- older adults and adult subjects -- were determined using the Kolmogorov-Smirnov test with a significance level $\alpha = 0.05$. One paired comparison: older adults' group relative to adults' group for each parameter, and again for each region adopted in the research. The experiment was designed so that the independent variables were the groups: older adult and adult, and the foot regions: the whole foot, heel, mid-foot, forefoot, and the hallux. Furthermore, the dependent variables were contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral. The control variable was the weight for each subject, which has been used for system calibration before the gait test commencement for each subject. The statistical differences of the demographic data of the subjects were evaluated by the Kolmogorov-Smirnov test, which has been pointed out in Table 3.2. The differences between the two selected groups for the plantar pressure parameters for all regions adopted in the study with a significance level $\alpha = 0.05$ have P-values as shown in Table 3.9. Additionally, the P-values for normalised plantar pressure parameters to study the influence of involving the subjects' weight while analysing these parameters on the comparison for the two cohorts are pointed out in Table 3.10. The statistical tests were performed on a desktop computer with the following features: Intel (R) Core 7 CPU and RAM of 8.0 GB. The model was coded in MATLab.

3.5 Foot region characteristics results

The results revealed statistically significant differences in the contact area parameter for the all specific regions selected beneath the human foot plantar in this study, except the hallux region, between the two groups participating: older adults and adults.

Generally, the whole foot region had the largest value of the contact area for the two groups within the in-shoe sensors among the selected regions in the research. This value was followed by the region of forefoot, and then the heel area. The results recorded the smallest contact area readings in both mid-foot and hallux regions.

The results revealed that the older adults had significantly higher contact area value than the adults group for the whole foot area with (P-value < 0.05), having mean contact area of the whole foot of the three middle steps of gait for older adults and adults of (125.33 ± 20.31, 122.65 ± 19.73 cm^2), respectively. Furthermore, it was found that there was a statistically significant difference (P-value < 0.05) for the contact area measure in both forefoot and heel regions between the two cohorts for which the contact area value was (forefoot: 66.06 ± 9.94, 62.8 ± 12.33 cm^2), (heel: 41.23 ± 5.86, 36.42 ± 4.65 cm^2) for older adults and adult subjects, respectively. In addition, a statistically significant variation with (P-value < 0.05) was found between the two selected groups within the mid-foot region wearing in-shoe sensors; however, the older adults group had lower contact area value in this specific region when compared to the adults group for which the contact area reading for older adults and adults was (18.25 ± 12.56, 23.43 ± 6.4 cm^2), respectively.

It is worth noting that there was no statistically significant change under the hallux area between the two selected groups. However, the older adults had higher contact area value when compared to the control group data: the adults group. Table 3.3 points out the comparison values between older adults and adults of contact area parameter along with graph, showing the difference between the two groups for all selected regions (Figure 3.5).

Table 3.4 illustrates the mean contact pressure measures for both groups: the older adults and the adults. Generally, the higher contact pressure value was found to be within the older adults group compared with the adults group for most of the regions selected in the study. However, there was statistically significant variation only in two regions, namely forefoot, and the hallux, having a significantly higher contact pressure value for older adults group (P-value < 0.05) than that of the adult group. The mean contact pressure value for older adults and adult subjects in the forefoot area was (219.46 ± 63.22, 167.12 ± 33.29 kpa), respectively. Additionally, the value of contact pressure for the hallux area was (170.99 ± 70.71, 133.74 ± 41.24 kpa), respectively. In contrast, the results revealed a lower contact pressure under the mid-foot region for older adults compared with the adults group. Figure 3.6 shows the contact pressure comparison between the older adults and adult subjects.

The highest force reading underneath the specific selected regions for both cohorts was recorded under the whole foot and forefoot regions, and then under the heel region. In contrast, the results revealed that the lowest force value readings were under the mid-foot and hallux regions. The mean force values with their standard deviation ranges for each region selected for both cohorts are presented in Table 3.5, and Figure 3.7. There was a significant difference with (P-value < 0.05) for the mean force of the three middle steps of the gait between the two groups participating: older adults and adults, recording a force value for the older adults group significantly higher than that of the adults group in the whole foot, heel, forefoot, and hallux regions. On the other hand, there was a statistical difference of (P-value < 0.05) in which the mean force was higher in the adults group compared with the older adults group under the mid-foot region. The mean force under the mid-foot area was (11.68 ± 13.04, 16.41 ± 8.93 kg) for older adults and adult subjects, respectively.

The foot loading data for the mean of peak plantar pressure along with the standard deviation values, for both groups: older adults and adult subjects, are depicted in Table 3.6. The comparison between the two groups for selected regions is presented in Figure 3.8.

The highest peak pressure reading was recorded under the whole foot and forefoot regions for both groups, followed by heel and hallux regions whereas the lowest peak pressure value amongst the selected regions was under the mid-foot region for both older adults and adult subjects.

There was a statistically significant difference in peak plantar pressure measures between the two groups, as observed under the specific selected regions at (P-value < 0.05); however, the results showed no significant difference under the heel region. The greatest difference of peak pressures between the older adults and adults groups was found under the forefoot and hallux regions.

The mean peak pressure measures in forefoot and hallux regions within older adults were (767.38 ± 277.36, 441.43 ± 304.42 kpa), respectively whereas these values were (448.05 ± 119.79, 268.67 ± 128.89 kpa), respectively for the adults group.

It is worth noting that the mean peak pressure measures of the three middle steps while wearing in-shoe sensors under the mid-foot region for older adults group was lower than that for the adults group. The mean peak pressure value beneath the mid-foot region was (124.69 ± 68.67, 172.33 ± 73.66 kpa) for older adults and adult participants, respectively.

In terms of force-time integral parameter, referred to as impulse, generally there were significant variations of foot characteristics in force-time integral measures between the two groups: older and adult participants with (P-value < 0.05), having a significantly higher for older adults than that of the adults group under most of the selected regions in the study. The mean force-time integral values for the older adults group in the whole foot, heel, forefoot, and hallux regions were (54.95 ± 10.12, 20.9 ± 6.33, 31.19 ± 7.71, and 2.96 ± 2.09 kg*sec), respectively while these values for the adults group were (42.38 ± 10.88, 17.3 ± 5.93, 20.42 ± 6.94, and 1.71 ± 0.95 kg*sec), respectively. In contrast, under the mid-foot region, the mean force-time integral readings for the older adults group were lower than that of the adults group with (3.05 ± 3.63, 4.62 ± 2.95 kg*sec), respectively. The means of force-time integrals along with the standard deviation ranges under the specific selected regions for both groups are presented in Table 3.7 and Figure 3.9.

The mean values of pressure-time integral for both groups: older adults and adults are displayed in Table 3.8. Figure 3.10 shows the foot loading of pressure-time integral comparison between the two cohorts. The highest mean pressure-time integral values for the older adults group were, in descending order, in the whole foot region 104.57 ± 24.75 kpa*sec, forefoot region 72.45 ± 15.12 kpa*sec, heel area 67.78 ± 17.92 kpa*sec, hallux region 36.4 ± 20.35 kpa*sec, and the mid-foot area 29.07 ± 12.29 kpa*sec. Additionally, the highest mean of the pressure-time integral within the adults was recorded under the whole foot region 82.61 ± 17.99 kpa*sec, followed by the heel region with mean value of 60.11 ± 18.69 kpa*sec, and then the forefoot and mid-foot regions by mean reading of (53.33 ± 15.51, 34.88 ± 12.09 kpa*sec), respectively. Finally, the lowest mean of pressure-time integral for adults group was found under the hallux region with value of 22.16 ± 10.97 kpa*sec.

Noticeably, there was a statistically significant variation in foot characteristics, the pressure-time integral, between the two groups: older adults and adult subjects. The mean pressure-time integral of the three middle steps performed by each participant while wearing in-shoe pressure sensors, for older adults' group reading was significantly higher than that in the adults' group under the whole foot region. Additionally, the results revealed statistically a significant difference between the two groups, pointing out higher values of the mean pressure-time integral for older group under the forefoot, heel, and hallux regions when compared to the adults group. However, the mid-foot region for the older adults group had a smaller reading in the mean pressure-time integral measures than that for the adults group. The differences between the two selected groups for the plantar pressure parameters for all regions adopted in the study with a significance level $\alpha = 0.05$ recorded P-values as shown in Table 3.9.

Table 3.3: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Contact Area	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	125.33	± 20.31	122.65	± 19.73
Heel	41.23	± 5.86	36.42	± 4.65
Mid-foot	18.25	± 12.56	23.43	± 6.40
Forefoot	66.06	± 9.94	62.80	± 12.33
Hallux	10.32	± 2.72	9.85	± 2.62

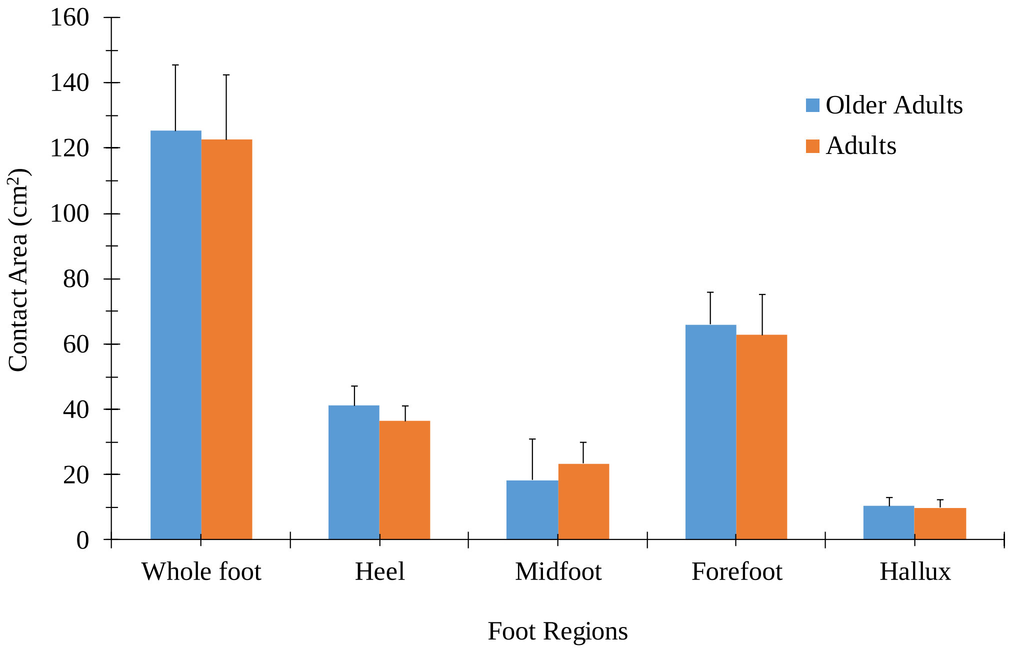

Figure 3.5: Mean and standard deviation of un-normalised contact area values of the three middle normal walking steps in (cm^2) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.4: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Contact Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	222.62	± 60.30	188.72	± 40.68
Heel	222.73	± 59.72	214.93	± 67.66
Mid-foot	84.37	± 35.68	95.13	± 38.58
Forefoot	219.46	± 63.22	167.12	± 33.29
Hallux	170.99	± 70.71	133.74	± 41.24

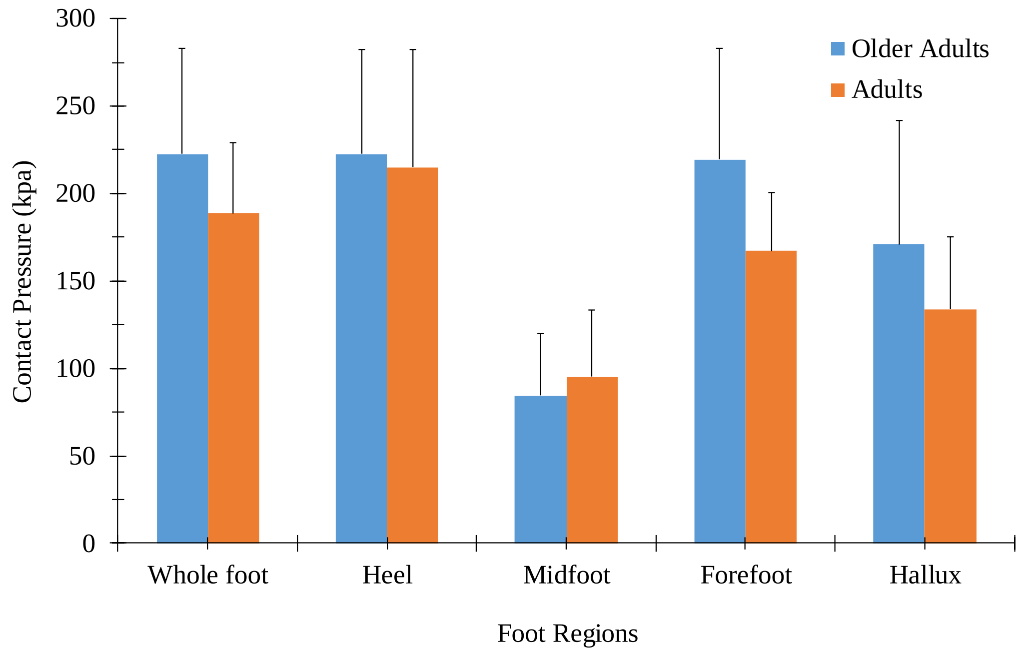

Figure 3.6: Mean and standard deviation of un-normalised contact pressure values of the three middle normal walking steps in (kpa) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.5: Mean values and standard deviations for the force in (kg) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Force	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	116.84	± 20.14	94.26	± 17.53
Heel	82.24	± 19.82	70.46	± 18.56
Mid-foot	11.68	± 13.04	16.41	± 8.93
Forefoot	114.78	± 22.48	88.27	± 19.12
Hallux	17.32	± 9.47	13.40	± 6.83

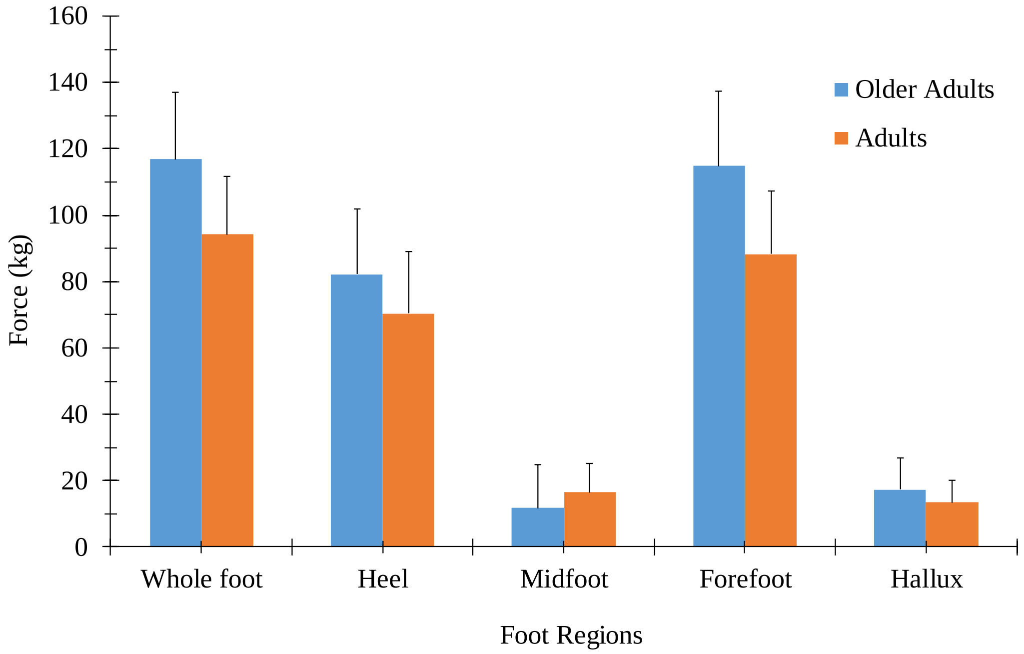

Figure 3.7: Mean and standard deviation of un-normalised force values of the three middle normal walking steps in (kg) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.6: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	770.73	± 273.09	494.04	± 125.52
Heel	493.40	± 170.11	427.22	± 139.87
Mid-foot	124.69	± 68.67	172.33	± 73.66
Forefoot	767.38	± 277.36	448.05	± 119.79
Hallux	441.43	± 304.42	268.67	± 128.89

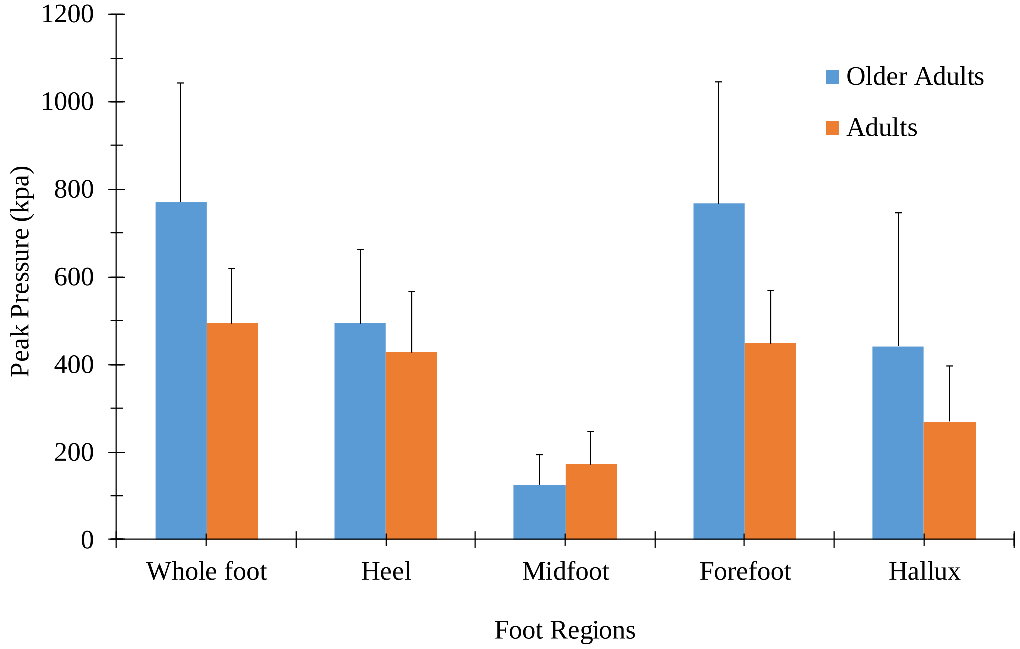

Figure 3.8: Mean and standard deviation of un-normalised peak pressure values of the three middle normal walking steps in (kpa) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.7: Mean values and standard deviations for force-time integral (FTI) in (kg*sec) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

FTI	Older Adults		Adults	
	Mean	SD	Mean	SD
Whole foot	54.95	± 10.12	42.38	± 10.88
Heel	20.90	± 6.33	17.30	± 5.93
Mid-foot	3.05	± 3.63	4.62	± 2.95
Forefoot	31.19	± 7.71	20.42	± 6.94
Hallux	2.96	± 2.09	1.71	± 0.95

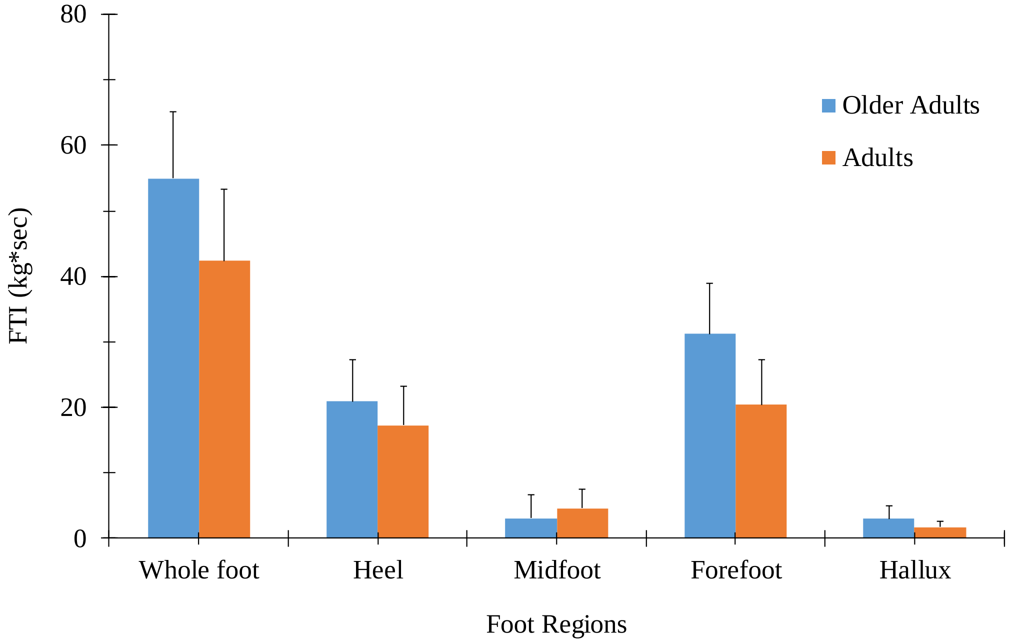

Figure 3.9: Mean and standard deviation of un-normalised force-time integral values of the three middle normal walking steps in (kg*sec) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.8: Mean values and standard deviations for pressure-time integral (PTI) in (kpa*sec) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

PTI	Older Adults		Adults	
	Mean	SD	Mean	SD
Whole foot	104.57	± 24.75	82.61	± 17.99
Heel	67.78	± 17.92	60.11	± 18.69
Mid-foot	29.07	± 12.29	34.88	± 12.09
Forefoot	72.45	± 15.12	53.33	± 15.51
Hallux	36.40	± 20.35	22.16	± 10.97

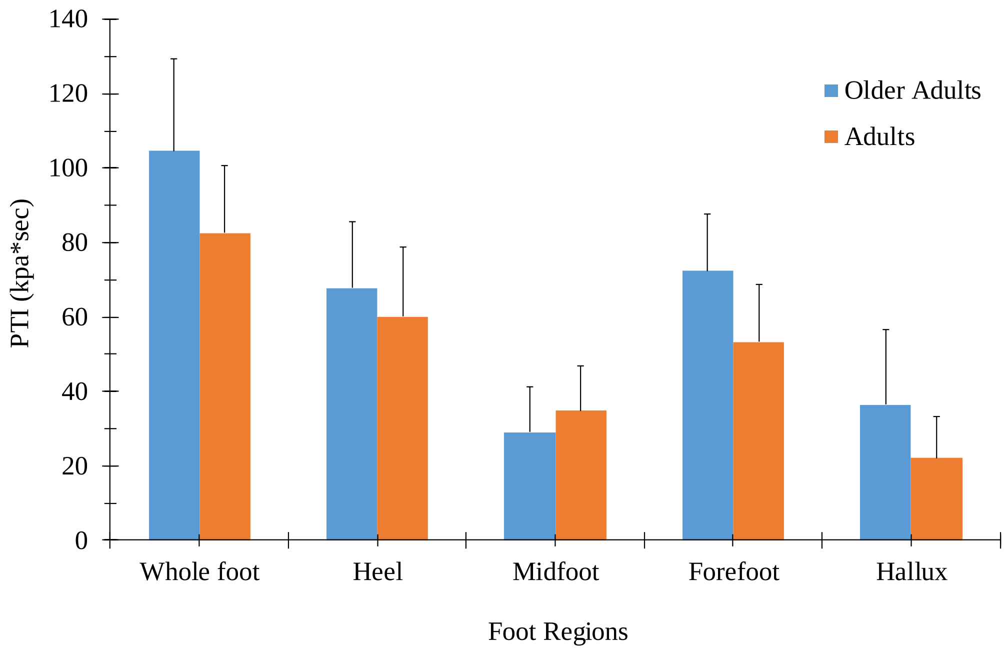

Figure 3.10: Mean and standard deviation of un-normalised pressure-time integral values of the three middle normal walking steps in (kpa*sec) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.9: Kolmogorov-Smirnov test P-values for the plantar pressure measurement comparison between older adult and adult groups under five selected plantar regions with a significance level α = 0.05.

	Whole foot	**Heel**	**Mid-foot**	**Forefoot**	**Hallux**
Contact Area (cm²)	0.0050	1.5787e-05	3.5652e-04	9.0587e-04	0.8931
Contact Pressure (kpa)	0.0796	0.7237	0.0796	1.3304e-04	0.0022
Force (kg)	5.0206e-06	0.0431	9.0587e-04	5.0206e-06	0.0222
Peak Pressure (kpa)	1.5138e-06	0.5313	0.0022	3.0141e-08	0.0050
FTI (kg*sec)	3.0141e-08	0.0222	9.0587e-04	3.0141e-08	0.0022
PTI (kpa*sec)	1.5787e-05	0.0431	0.0796	1.5138e-06	9.0587e-04

3.6 Discussion

The measurement of plantar pressures during walking can assist in the evaluation of the foot in both clinical and research fields, particularly for older adults with different foot conditions (Menz et al., 2006a). The abnormal distribution of plantar pressure patterns measured under dynamic conditions can contribute to the development of a number of foot impairment conditions. For instance, elevated pressure beneath the plantar encountered by older people can lead to the development of tissue injuries, leading to deteriorating foot conditions such as: forefoot pain, plantar ulceration, and stress fractures under the metatarsal bones (Burnfield et al., 2004; Bus et al., 2005; Menz and Morris, 2006a).

Plantar pressure parameters were recorded for selected subjects while wearing in-shoe pressure sensors in the first session. The second session was conducted one week after the first one; hence, ensuring the required reliability of the actual plantar pressure parameters for both groups has been obtained (Zammit et al., 2010), particularly for the older adults' group. The assessment of more than one test performed in two sessions might be pertinent for consideration as far as the main concern of this study is the older age (Franco et al., 2018). Furthermore, the duration of one week between the two sessions was adopted to assure that subjects' gait characteristics had not altered in a measurable way (Zammit et al., 2010). The participants were requested to wear an appropriate shoes size with an in-shoe sensor attached to these shoes to perform the gait test on a 10-metres long walkway at their normal walking speed to measure the plantar parameters under five selected regions, namely the whole foot, heel, mid-foot, forefoot, and hallux (as appeared in Figures 3.1 - 3.3).

The study aimed to explore the variability in a number of plantar pressure parameters for a number of selected main regions, which cover the entire foot plantar to compare older adults and adult subjects in terms of measuring their plantar pressure patterns, particularly comparing the mean of the three middle steps while adopting F-scan sensors, including 960 individual pressure sensing locations, for the two groups who participated in this study. The plantar pressure parameters, namely the contact area, contact pressure, force, peak plantar pressure, force-time integral, and pressure-time integral were measured for data analysis in these main regions due to the importance of examining the variability in foot loading patterns with advancing age. Therefore, it is important to underscore the variation in foot loading patterns between older adults, prior to attaining the elderly stage, with the control data being the adults group. Being able to understand the gait differences can be crucial for avoiding the development of foot conditions sustained with advancing age.

Several studies have indicated the difference of plantar pressure measurements related to the age factor (Franco et al., 2018; Hessert et al., 2005; Machado et al., 2016); however, these studies have utilised a different variety of methods to measure and evaluate these parameters. Contact pressure values, measured in this study, were higher for the older adults group, and lower for the adults group, particularly under the forefoot and hallux regions. These findings are consistent with the study investigated by Franco et al. (2018), who have identified elevated plantar pressure levels under the forefoot area for older adults group when compared to both adults and children's groups, analysing their gait during barefoot walking using a pressure mat system (Matscan, Tekscan Inc., Boston, MA, US) designed to place halfway in a 9-metre walkway.

Additionally, the high pressure values distributed on the region of hallux for older adults group, in our findings, illustrated an association with the foot difficulties encountered with advancing age under this foot plantar region (Hannan et al., 2013; Martínez-Nova et al., 2010). This can impair the gait stability, and accordingly the walking balance, which may increase the risk of falling for this age group (Menz et al., 2005a).

Noticeably, results for the older adults' group showed lower pressure measures under the mid-foot area when compared to the adults group, the finding was in line with the studies carried out by Kernozek and LaMott (1995), and Scott et al. (2007), and in male comparison research between adults and older people, aged over sixty years (McKay et al., 2017).

Our research findings demonstrated that the older adults' group had higher force values when compared with the adults' group at the whole foot, heel, forefoot, and hallux regions while wearing in-shoe sensor attached to an appropriate shoes size for each subject; however, the older adults group had lower force measures under the mid-foot area compared to the adults group. The finding was compatible to some extent with the research performed by Scott et al. (2007), who found that older people group had higher maximum force in their total foot and under the first metatarsal bone, and lower force under the heel, mid-foot, and hallux regions. The study assessed the plantar pressure values for subjects using a MatScan® system during barefoot walking. Regardless of the variety in the adopted methods between this study and the one of our own research, leading to some differences with the outcomes obtained by each of them, it might be believed that higher forces measured within older adults group in a number of plantar regions of our own research was attributed to higher average weights for older adults group when compared to those of the adults group who participated in this study, as highlighted in few studies undertaken previously (Birtane et al., 2004; Mickle et al., 2015; Neri et al., 2017).

In Figure 3.8, the results exhibited that, within the older adults' group, higher peak pressure values occurred under the forefoot region, followed by the heel and mid-foot areas. These findings were in accordance with the study accomplished by McKay et al. (2017), and Franco et al. (2018). This would account for the alteration in foot sensitivity for older people, in particular, the heel and mid-foot areas. As a consequence, the forward shift strategy was a trend to shift older people's plantar pressures from the insensitive heel region to the forefoot area to eventually maintain balance while performing weight bearing tasks (Franco et al., 2018; Machado et al., 2016; McKay et al., 2017).

Additionally, the older adults' group displayed significantly higher peak pressure measures than the adults' group underneath the whole foot, forefoot, and hallux regions. In contrast, the mean mid-foot peak pressure for the older adults group was lower than that of the adults' group, reinforced by the results from research undertaken by McKay et al. (2017), which aimed to establish a reference for plantar pressure values using an Emed platform system for different age groups. Our findings of this investigation highlighted that the excessive peak pressures in older adults group may be explained by the age-related changes of the ankle-foot mechanical properties and also the changes in the characteristics of plantar soft tissue (McKay et al., 2017). Furthermore, in the older adults' group, excessive peak pressures distributed under the forefoot region, including the hallux area than those under the heel and mid-foot areas during gait can result in foot injuries and lead to the development of ulceration under these regions. This would account for the prevalent conditions in older adults' forefoot site, including the area under the metatarsal bones, which in turn, might hinder their normal gait (Kwan et al., 2010; Wang et al., 1999). Another study performed by Frykberg et al. (1998) have ascertained the association of higher plantar pressures distributed under the foot of diabetic patients with the development of ulceration in their plantar (Abri et al., 2019; Bus and de Lange, 2005; Pham et al., 2000; Veves et al., 1992).

As described previously in the result section, older adults group had higher force-time integral values under the whole foot, heel, forefoot, and hallux regions; however, the mid-foot area showed lower force-time integral values in the older adults' group when compared to the adults' group, as appeared in Figure 3.9. The outcomes of the study undertaken by McKay et al. (2017) was correspond with those of our study. Their study emphasised that higher pressure and force measures found in the older adults' group may explain the prevalence of foot plantar pain, that developed with advancing age (Bosch et al., 2009). Moreover, the result of our study was similar to some extent to that conducted by Scott et al. (2007). The latter study was designed to investigate the aging effect on plantar pressure and force patterns. It was found that the force of the total foot and underneath the first metatarsal bone was higher for older people whilst the mid-foot force for the same group was lower than that for the young group.

Our result of comparable pressure-time integral measures between older adult and adult groups exhibited a number of remarkable findings, as shown in Figure 3.10. Difference in the mean pressure-time integral values was noticeable, with the older group significantly displaying higher measures under the whole foot, heel, forefoot, and hallux regions. These findings were supported by the results of the study conducted by McKay et al. (2017).

It is postulated that the trend from older adults on a longer contact time might diminish the peak pressure recordings associated with this group, as is supposed to happen according to study undertaken by Segal et al. (2004). The study assessed peak plantar pressure in relation to walking speed. The study determined that increasing the speed was significantly associated with raising peak plantar pressure values in a number of regions involved in that study, namely heel, (medial, central, and lateral) forefoot, and the hallux. However, the results of our study showed higher peak pressure measures, as mentioned previously underneath the regions selected in our study relating to the outcome of older adults, and accordingly, the results showed higher pressure-time integral under the same regions during loading phases of gait. The results were confirmed by previous research carried out by Melai et al. (2011), who pointed out a high concordance between peak pressures and pressure-time integral measures.

Pressure-time integrals, referred to as integrals, provide in general an indication of the pressure amount in relation to the time that pressure presented on the foot plantar surface, and in turn to any region deemed to be selected beneath the human plantar surface. This doctoral research presented higher integrals under specific selected regions for the older adults' group with relation to their findings, as previously reported in the result section. This means that older adults exerted more pressure together with a longer period of time underneath their whole foot, heel, forefoot, and hallux regions when compared to the adults' group outcome; as a consequence, more pressure applied for a longer time during gait might develop foot injuries in these regions in particular underneath the forefoot and hallux regions, which showed the greatest difference related to control group data, leading to the development foot impairment conditions sustained by older adults (Kwan et al., 2010).

It is worth noting that the older adults' mid-foot region underwent lower integrals than those of adults, a result that was in line with that conducted by McKay et al. (2017).

In terms of the demonstration of the gait patterns, taking into consideration the percentage of the averaged weight for each group which can alter the plantar pressure distribution, it is necessary to discuss whether including the human weight factor when analysing plantar pressure distribution would have an influence on changing the plantar pressure measurement levels for the two groups being compared. A number of studies have included the normalisation process, depending on their research requirements (Bosch et al., 2009; Castro et al., 2013; Hessert et al., 2005; Keijsers et al., 2013; Mickle and Steele, 2015). To our knowledge, these studies utilised normalised plantar pressure patterns for either specific foot pathology to be compared with the control group, or to compare groups of different age stages with various pressure pattern analysis systems; however, these age groups are different to the ones adopted in our own study, which has been conducted for healthy older adults aged 65-80 years and adults aged 25-45 years without any specific known foot conditions, using F-scan in-shoe pressure sensor insoles.

There is a clear association between the age and the prevalence of foot problems and deformities that can alter plantar pressure patterns (Menz et al., 2007). The alteration is more likely to limit the equilibrium control, necessary for maintaining the gait stability (Huxham et al., 2001; Woollacott et al., 1997). Maintaining an adequate gait stability is imperative for quality in the daily life of older people. Impaired balance and accordingly gait stability for this age group is relevant to increased incidence level of falls (Lord et al., 2007; Pijnappels et al., 2008; Rubenstein, 2006; Yoshida-Intern, 2007), leading to lack of function and loss of independence (Berg et al., 1997; Stevens, 2005).

Additionally, as the subject's weight is likely to increase with advancing age (Janssen et al., 2007; Zamboni et al., 2005), and as we have pointed out from the demographic properties collected for subjects of both groups, older adults indicated significantly higher weight values with (P-value < 0.05) when compared to the adult subjects that can inaccurate outcomes resulting from plantar pressure measurements of the two selected cohorts. Previous studies emphasised that increased contact and peak pressure measures were associated with increased human body weight (Birtane and Tuna, 2004;

Butterworth et al., 2015; Hills et al., 2001), possibly leading to an unreasonable comparison. Consequently, the study suggested that normalised plantar pressure parameters based on the percentage of the averaged weight for each group would be adopted in this study in order to obtain a robust and meaningful comparison of dynamic plantar pressure patterns between older adults and adult subjects, wearing in-shoe sensors. This was to investigate whether there are changes in gait measurements of this comparison with relate to initial data comparison conducted for both groups. That was the second purpose required to be achieved. The P-values for normalised plantar pressure parameters to study the influence of involving the subjects' weight with analysing these parameters on the comparison between the two cohorts are pointed out in Table 3.10.

An insole based assessment system to measure normalised plantar pressure parameters has been shown in Figures 3.12 – 3.16. These figures depict the comparative plantar pressure distribution values of contact pressure, force, peak pressure, force-time integral, and pressure-time integral between older adults and adult subjects, taking into account these parameters as a percentage of the averaged weight for each group that hypothetically might have an influence on the amount of pressure parameters distributed in selected plantar regions. It is worth noting that the contact area has been normalised based on the contact area for each specific region to the whole contact area of the total foot calculated for each subject, as shown in Figure 3.11.

It is plausible that normalised plantar pressure measures, according to the percentage of the averaged weight, demonstrate relative changes in differences between the two groups analysed for initial data comparison. However, the weight-normalised plantar pressure measurements showed no major variations with respect to initial un-normalised data comparison in terms of higher plantar pressure values under most of selected plantar regions for older adults.

Contact pressure values, taking into account the weight factor when analysing the differences between the two selected groups, showed similar comparison to the un-normalised parameters under most of the plantar regions, except the heel area, which had lower contact pressure measures for older adults, compared to the control group data with no mentioned significant difference. On the other hand, the normalised force comparison showed approximately the same outcome to that held for the preliminary measured force values.

Apparently, peak pressure values increased significantly with advancing age, particularly under the forefoot and hallux regions (Bosch et al., 2009), compatible with the findings of the present study. This can potentially be an indicator of foot damage (Frykberg et al., 1998; Keijsers et al., 2013). Force-time integral findings to include the averaged weight for each group when analysing the measured data of the present study illustrated comparison levels similarly to that mentioned earlier, conducted for initial measured plantar parameters.

Normalised pressure-time integral results displayed a similar comparison to the one conducted to the initial measured plantar parameters, in particular the regions of forefoot and hallux that showed significantly higher values for older adults relative to adult subjects, emphasising that older people undergo elevated integral measures beneath these areas during walking. Obviously, the appearance of plantar ulceration can be attributed to an excessive amount of pressure-time integral, which is the area under the time curve of peak pressure (Bus et al., 2013). Furthermore, research has shown that excessive integral values distributed underneath the forefoot and hallux areas can result in increased forefoot pain, and possibly in developed foot complaints for this age group (Keijsers et al., 2013). Moreover, the presence of hallux valgus was found to be associated with altered gait patterns (Mickle et al., 2009), affecting the forefoot functional ability in older male adults (Kavlak, 2015). A number of studies have researched this common foot condition, which has been shown to increase with advancing age (Hida et al., 2017; Koller et al., 2014).

To sum up, there were similarities between a weight-normalised data comparison with the one held to initial measured parameters; however, there were variances in terms of the plantar pressure measurement differences between the two selected groups for normalised data, relative to the initial un-normalised data. Thus, even with the consideration of individuals' weight in conjunction with analysing plantar pressure parameters to ensure a compatible set of data, the findings revealed higher plantar pressure values for most of regional plantar regions for older adults when compared to the adult subjects.

Table 3.10: Mean values and standard deviations for normalised contact area parameter in (cm2) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Contact Area	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	125.33	± 20.31	122.65	± 19.73
Heel	33.22	± 3.95	29.99	± 3.55
Mid-foot	13.92	± 8.05	18.97	± 3.76
Forefoot	53.07	± 5.84	51.04	± 3.40
Hallux	8.29	± 2.05	8.04	± 1.91

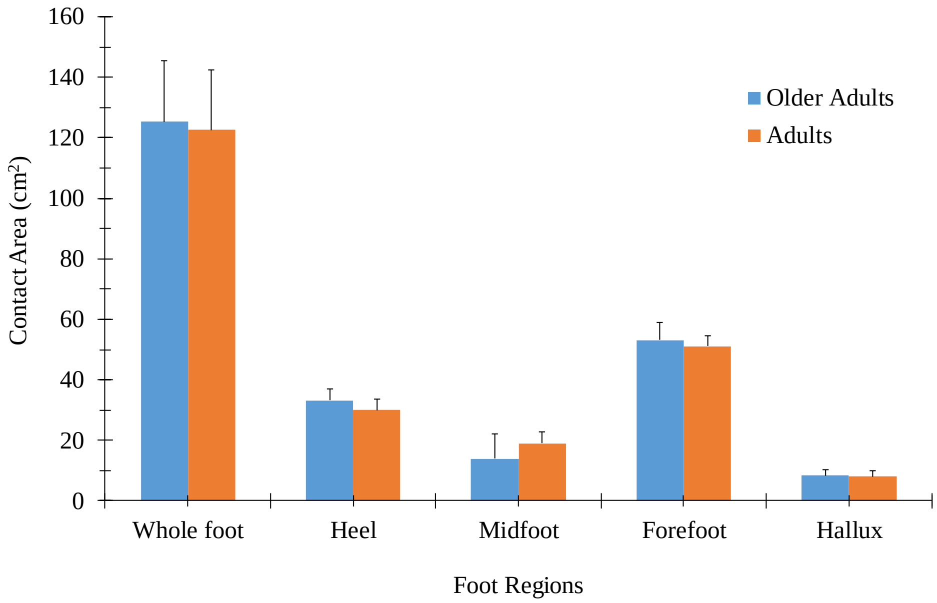

Figure 3.11: Mean and standard deviation of normalised contact area values of the three middle normal walking steps in (cm^2) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.11: Mean values and standard deviations for normalised contact pressure parameter in (kpa) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Contact Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	270.66	± 73.32	261.38	± 56.34
Heel	270.79	± 72.60	297.68	± 93.72
Mid-foot	102.57	± 43.39	131.75	± 53.43
Forefoot	266.82	± 76.86	231.46	± 46.11
Hallux	207.89	± 85.97	185.24	± 57.13

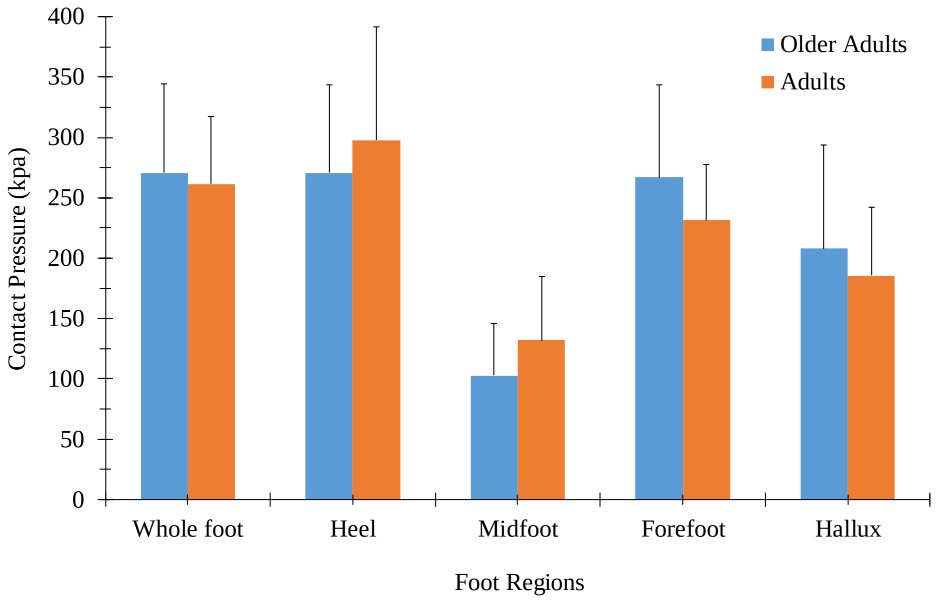

Figure 3.12: Mean and standard deviation of weight-normalised contact pressure values of the three middle normal walking steps in (kpa) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.12: Mean values and standard deviations for normalised force parameter in (kg) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Force	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	142.05	± 24.48	130.56	± 24.28
Heel	99.99	± 24.09	97.59	± 25.70
Mid-foot	14.21	± 15.85	22.72	± 12.37
Forefoot	139.55	± 27.33	122.26	± 26.48
Hallux	21.06	± 11.51	18.56	± 9.45

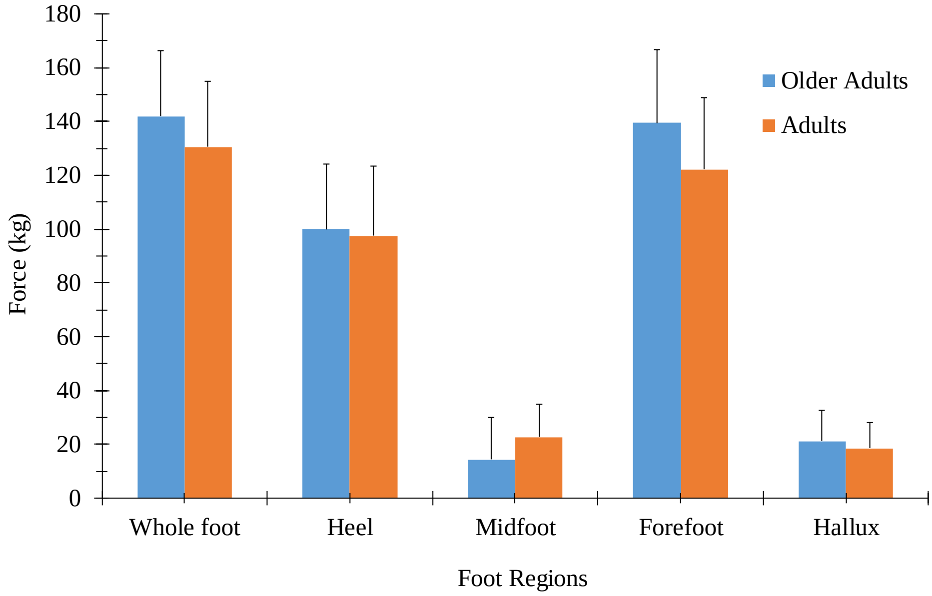

Figure 3.13: Mean and standard deviation of weight-normalised force values of the three middle normal walking steps in (kg) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.13: Mean values and standard deviations for normalised peak pressure parameter in (kpa) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	937.06	± 332.02	684.27	± 173.86
Heel	599.88	± 206.82	591.71	± 193.72
Mid-foot	151.60	± 83.49	238.69	± 102.03
Forefoot	932.98	± 337.22	620.57	± 165.92
Hallux	536.70	± 370.12	372.11	± 178.51

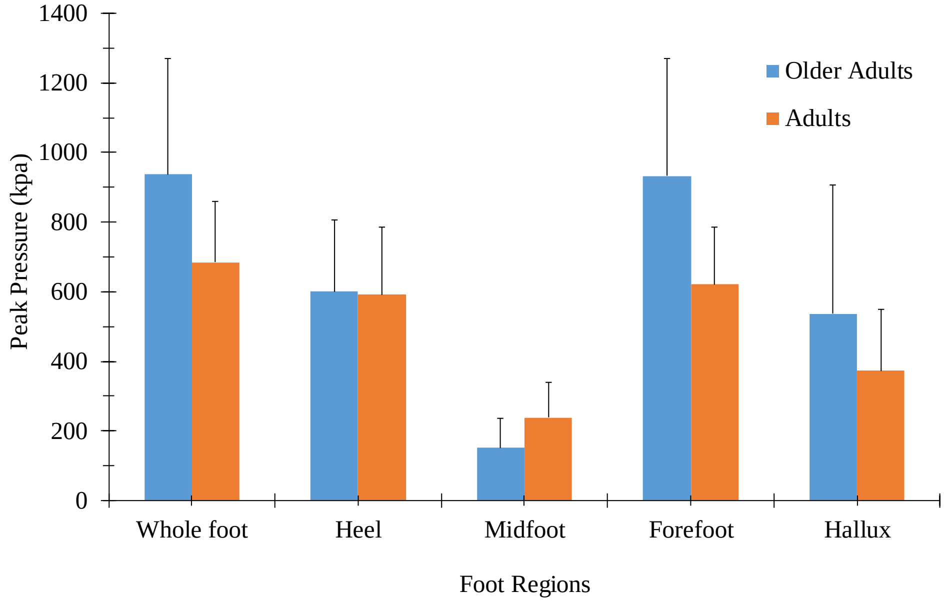

Figure 3.14: Mean and standard deviation of weight-normalised peak pressure values of the three middle normal walking steps in (kpa) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.14: Mean values and standard deviations for normalised force-time integral (FTI) parameter in (kg*sec) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

FTI	Older Adults		Adults	
	Mean	SD	Mean	SD
Whole foot	66.80	± 12.30	58.69	± 15.06
Heel	25.41	± 7.70	23.96	± 8.21
Mid-foot	3.70	± 4.41	6.40	± 4.09
Forefoot	37.93	± 9.38	28.28	± 9.62
Hallux	3.60	± 2.54	2.37	± 1.31

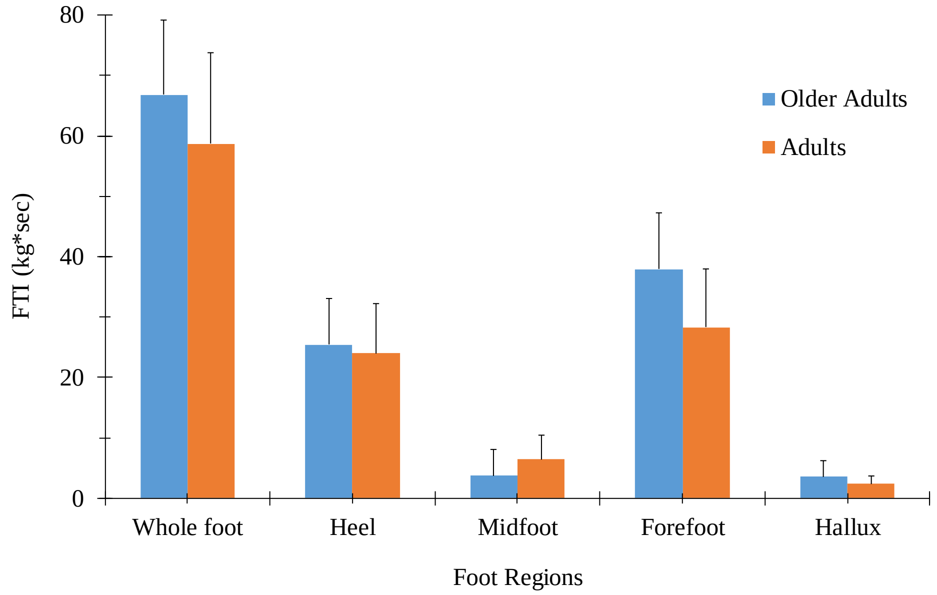

Figure 3.15: Mean and standard deviation of weight-normalised force-time integral values of the three middle normal walking steps in (kg*sec) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.15: Mean values and standard deviations for normalised pressure-time integral (PTI) parameter in (kpa*sec) for older adult and adult groups of the three middle steps of normal walking trials for two sessions for each subject in five selected regions.

PTI	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Whole foot	127.14	± 30.09	114.42	± 24.91
Heel	82.40	± 21.79	83.25	± 25.88
Mid-foot	35.34	± 14.94	48.31	± 16.75
Forefoot	88.09	± 18.39	73.86	± 21.48
Hallux	44.25	± 24.74	30.69	± 15.19

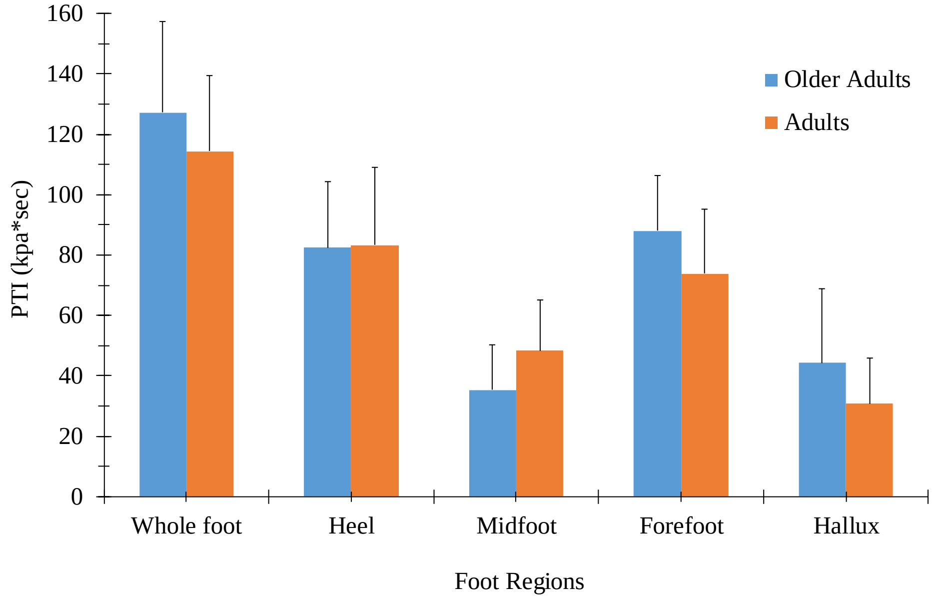

Figure 3.16: Mean and standard deviation of weight-normalised pressure-time integral values of the three middle normal walking steps in (kpa*sec) for comparison between older adult and adult groups conducted in two sessions for each subject in five selected plantar regions during the whole stance phase.

Table 3.16: Kolmogorov-Smirnov test P-values for the normalised plantar pressure measurement comparison between older adult and adult groups under five selected plantar regions with a significance level α = 0.05.

	Whole foot	**Heel**	**Mid-foot**	**Forefoot**	**Hallux**
Contact Area (cm^2)	0.0050	3.5652e-04	4.7066e-05	0.0050	0.5313
Contact Pressure (kpa)	0.8931	0.1393	0.0022	0.1393	0.2307
Force (kg)	0.0222	0.8931	1.3304e-04	0.0022	0.1393
Peak Pressure (kpa)	0.0022	0.7237	4.7066e-05	1.5787e-05	0.0796
FTI (kg*sec)	0.0050	0.3613	1.3304e-04	5.0206e-06	0.0222
PTI (kpa*sec)	0.0222	0.8931	0.0050	9.0587e-04	0.0022

3.7 Conclusion

The study was conducted to investigate the influence of plantar measurement during the whole stance phase of the gait cycle, wearing in-shoe sensors, on foot complaints sustained with advancing age through the comparison undertaken between two age groups: older adults and adult subjects. Additionally, the research was carried out to find out whether including subjects' weight when analysing research parameters had an influence on changing the level of differences of plantar pressure patterns between the two cohorts. The research provided an evaluation of the human gait while adopting in-shoe sensor systems for older people with the control data: the adults' group. The pressure patterns measured during the entire stance phase were substantial in terms of thoroughly enhancing the pressure distribution visualisation of the whole foot plantar, thus assisting the provision of insights into plantar pattern variations due to the aging factor, which can contribute to understanding the causes leading to a lack in maintaining the balance necessary for older people during gait. Providing clear understanding can support older people through foot wear design optimised to suit their needs or via clinical interventions designed to avoid the development of foot conditions. The next chapter addresses the gait loading patterns comparison for a number of healthy older adults between level and inclined surfaces.

CHAPTER FOUR

LOADED GAIT PHASE COMPARISON FOR OLDER ADULTS AGED 65-80 YEARS BETWEEN LEVEL AND INCLINED SURFACES

4.1 Introduction

Despite the fact that older people are able to perform independent walking, their capability to maintain balance control could deteriorate substantially, particularly with unexpected events that might occur during gait such as trips and slips, the leading causes of losing the control of balance, made worse with advancing age. Hence, falls in the older adult group could increase. Balance control can be influenced by the tasks undertaken and also by the environment in which these tasks take place. Furthermore, balance control is likely to be affected by different actions and environments due to the alteration in the biomechanics required to maintain the body stability. It is possible that stepping uphill and downhill is more challenging than performing normal walking with older adults. Measuring plantar pressure distributed beneath the human foot plantar wearing in-shoe pressure sensors has been adopted in this study which can enable a comprehensive examination of the distribution of the body weight within a number of older adult subjects for various gait conditions, including walking on level surfaces, uphill and downhill walking steps, and to study the influence of these tasks on the body balance and stability with advancing age. Twenty subjects were recruited in the study to perform gait trials for different tasks: level walking, uphill and downhill walking steps at their self-selected speeds using pressure sensor insoles as a measurement system for capturing plantar pressure patterns underneath five anatomically defined foot plantar regions. The results showed higher plantar pressure measurements, including contact pressure, peak pressure, force-time integral, and pressure-time integral values, particularly under the whole foot, forefoot, and hallux regions accompanied by lower contact area measures beneath these areas for uphill walking condition compared to level walking. For downhill walking tasks, the results revealed an excessive increase in peak pressure, force-time integral, and pressure time integral values underneath the whole foot, forefoot, and hallux regions in relation to that of level walking condition. The distribution of plantar pressure measurements undertaken for older individuals can provide an assessment for these different tasks, which can be useful to be adopted as a reference value for the clinical domain for the pathological diagnosis and injuries treatment provided for older people of the same age stage in relation to these activities.

4.2 Background

The ability of the balance task during standing for older adults has been shown to be sufficiently maintained by the activities of the muscles of the human ankle (Huxham et al., 2001; Nashner, 2014; Winter, 1995a; Woollacott et al., 1997). However, the capability for maintaining the balance during walking has been found to have declined due to the fact that the activity of the human ankle muscles alone is insufficient to attain the required control of the body during gait with advancing age, particularly when hazardous events take place such as slips, and trips (Winter, 1995a; Woollacott and Pei-Fang, 1997). Falls sustained by older adults are associated with a higher incidence of these events (Woollacott and Pei-Fang, 1997), especially for people with different foot deformities (Mickle et al., 2009). Additionally, the ability to maintain the required balance during gait can be affected by the characteristics of the action or the task being performed (Carry et al., 1998; Huxham et al., 2001). Hence, the challenge of balance control might increase when walking on uphill and downhill planes rather than walking on level surfaces, in particular for older people.

Plantar pressure measurements have been evaluated during gait on uneven terrains such as up slopes, down slopes, upstairs, and downstairs. Previous studies have been implemented to investigate dynamic plantar pressure during various ambulatory activities for patients with diabetic neuropathy (Kästenbauer et al., 1995; Maluf et al., 2004). The purpose of these studies was to assess plantar pressure distribution for level walking, which can assist in supporting the clinical evaluation to monitor the variations in levels of stress relative to other functional tasks performed by a group from those patients. In addition, a number of studies have examined plantar pressure distribution during level walking, compared to stair ascent and descent; however, these studies were performed for young adult subjects (Kim et al., 2013; Rao et al., 2012; Wervey et al., 1997). The results found that plantar pressure measures were influenced by foot region, and the task being performed.

Additionally, a limited number of studies have investigated plantar pressure distribution variations between level walking and both walking tasks: uphill and downhill walking steps (Grampp et al., 2000; Ho et al., 2010; Mattar et al., 2015); however, these studies were conducted for young adults, with some specific requirements in their methods that might limit the outcomes.

Importantly, previous research showed that slope walking has a greater risk than stair walking (Sheehan et al., 2012). To our knowledge, there is a lack of standard dynamic plantar pressure patterns as a comprehensive set for healthy older adult subjects during normal gait, including walking on a level surface, and uphill and downhill walking steps. Therefore, the aim of this research was to establish a reference value of plantar pressure parameters distributed under five foot regions covering the whole plantar surface. The reference value was collected on a measurement walkway while walking on level and inclined surfaces for a group of older adult individuals, conducted via a session of gait test measurements through three gait trials for each condition selected in the current work wearing pressure sensor insoles.

4.3 Methods

4.3.1 Participants

Twenty subjects were recruited in the study, who were older adults aged 65-80 years (mean age 72.3 ± 5.16 years, weight 82.25 ± 9.34 kg, height 173.55 ± 8.72 cm, and BMI 27.44 ± 3.76 kg/m^2). Subjects had no lower-limb injuries or complaints, including the foot. Table 4.1 shows the demographic data of the twenty subjects participating in the study. The mean contact time of the entire stance phase, comprising the three gait trials conducted for each individual under the three functional activities: level walking, and uphill and downhill gait steps was (0.71 ± 0.08, 1.18 ± 0.30, 1.21 ± 0.47 sec), respectively, as it appears in Table 4.2. The participation of the human subjects in this research was conducted under an approved ethical clearance application form (H18REA160) obtained from University of Southern Queensland Ethics Committee.

4.3.2 Equipment and protocol

The study utilised an in-shoe 3000E F-scan® pressure sensor (Tekscan, Boston, MA) system sampled at 100 Hz to capture plantar parameters, namely contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral. Informed consent forms have been signed by subjects who participated in the study. Demographic data, such as age, weight, height, and gender were collected from participants. A self-captured way was conducted to collect plantar pressure measurements.

Standard shoes of different sizes were provided so that each subject had to wear an appropriate size with an in-shoe 3000E F-scan® sensor sandwiched inside, as appears in Figure 4.1. F-scan pressure sensors have been adopted in the current study to reflect reliable gait patterns for older adults during various functional activities, namely level walking, and uphill and downhill walking steps as these sensors can be suited for various functional indoor and outdoor tasks, including a broad usage in sport activities (Burnfield et al., 2004; Mei et al., 2015). The pressure sensor insole allows the subjects to perform the natural gait freely during the walking tests as it can be easily embedded in the shoe to assess plantar pressure distributed between the human foot and the shoe (Ledoux et al., 2013; Razak et al., 2012). Hence, the study suggested using them in the current work because the main study focus is older people. No significant differences in plantar pressure measurements were detected between males and females in a number of previous studies (Hallemans et al., 2006; Hennig et al., 1994; Kanatli et al., 2008; Murphy et al., 2005; Phethean et al., 2012), with some studies showing few significant differences (Kandil et al., 2014; Putti et al., 2010). Consequently, gender-related aspects have not been placed into consideration when selecting subjects in the current research. However, due to different opinions regarding gender-related plantar pressure distribution variations, further research for future work will focus on gender influence on plantar pressure measurements during different walking tasks (Deepashini et al., 2014). The measurement accuracy for these sensors has been referred to in the methods section of chapter 3. The pressure sensor sheets were precisely taped with the sole of the shoes to prevent any slip while performing the walking, which was particularly important for uphill and downhill walking steps, in order to achieve a reliable measurement (Razak et al., 2012). The F-scan pressure insoles were calibrated before the walking trials of the three gait tasks for each participant according to the manufacturer's guidelines.

The study procedures were demonstrated to each participant prior to the commencement of each walking task. In addition, the participants were given a period of time to practise the gait trials in relation to each specific gait task in order to become familiar with the study procedures. Firstly, subjects performed a standard gait on a level surface along a 10-metre walkway, Figure 4.2. Then, they performed uphill and downhill walking steps, as shown in Figures 4.3, and 4.4. For each of these tasks, participants performed three consecutive gait trials at their self-selected walking speeds. Three gait trials for each walking activity were found to be sufficient to ensure adequate reliability of plantar pressure measurements (Hughes et al., 1991; van der Leeden et al., 2004; Zammit et al., 2010).

The gait tests were undertaken at the University of Southern Queensland laboratory. The plantar measurements were collected using FSCAN Research, version 6.7 software for a number of specified foot regions, namely the whole foot, heel, mid-foot, forefoot, and the hallux to study the foot loading pattern variations for the entire stance phase of the gait cycle for twenty older adult individuals under the three walking conditions: level, uphill and downhill walking steps. Figure 4.5 shows the data collection process used in this study for capturing plantar pressure parameters for the older adult group in order to compare between level with uphill and downhill walking conditions.

Table 4.1: Demographic properties for twenty older adult individuals, showing the age in (years), weight in (kg), height in (cm), body mass index (BMI) in (kg/m^2).

	Age	Weight	Height	BMI	Shoes Size	Gender	Age Stage
Subject 1	73	67	171	22.91	9	Male	Older Adult
Subject 2	74	71	173	23.72	9	Male	Older Adult
Subject 3	65	77	163	28.98	9	Female	Older Adult
Subject 4	69	64	164	23.80	8	Female	Older Adult
Subject 5	80	75	180	23.15	11	Male	Older Adult
Subject 6	78	78	182	23.55	11	Male	Older Adult
Subject 7	80	87	183	25.98	10	Male	Older Adult
Subject 8	78	91	180	28.09	10	Male	Older Adult
Subject 9	65	91	168	32.24	9	Male	Older Adult
Subject 10	66	94	170	32.53	9	Male	Older Adult
Subject 11	67	80	178	25.25	9	Male	Older Adult
Subject 12	68	83	180	25.62	9	Male	Older Adult
Subject 13	78	76	181	23.20	9	Male	Older Adult
Subject 14	76	79	179	24.66	9	Male	Older Adult
Subject 15	75	90	175	29.39	8	Male	Older Adult
Subject 16	74	92	177	29.37	8	Male	Older Adult
Subject 17	73	80	150	35.56	8	Female	Older Adult
Subject 18	70	93	178	29.35	9	Male	Older Adult
Subject 19	72	97	179	30.27	9	Male	Older Adult
Subject 20	65	80	160	31.25	9	Female	Older Adult

Table 4.2: Contact time of the stance phase for twenty older adult individuals, showing the contact time for level, uphill and downhill functional activities in (sec) along with P-values with a significance level α = 0.05, showing the significant differences between level and uphill, and level with downhill walking tasks using Kolmogorov-Smirnov tests.

Contact time	Level	Uphill	Downhill
Subject 1	0.65	0.97	0.95
Subject 2	0.66	1.03	0.94
Subject 3	0.69	1.42	1.40
Subject 4	0.59	1.31	3.01
Subject 5	0.69	1.11	0.91
Subject 6	0.66	0.91	1.06
Subject 7	0.79	1.54	1.23
Subject 8	0.75	1.30	1.29
Subject 9	0.63	0.99	0.72
Subject 10	0.75	0.84	0.86
Subject 11	0.80	1.15	1.12
Subject 12	0.80	1.04	1.08
Subject 13	0.73	0.95	1.02
Subject 14	0.89	1.09	1.16
Subject 15	0.65	1.25	1.30
Subject 16	0.75	1.17	1.23
Subject 17	0.80	2.11	1.41
Subject 18	0.69	1.16	1.09
Subject 19	0.69	1.49	1.46
Subject 20	0.59	0.85	0.91
Mean	0.71	1.18	1.21
SD	0.08	0.30	0.47
P-values		4.7406e-09	3.6296e-08

Figure 4.1: An in-shoe 3000E F-scan® pressure sensor (Tekscan, Boston, MA) system.

Figure 4.2: An older subject wearing in-shoe 3000E F-scan® sensors to perform level walking condition.

Figure 4.3: An older subject wearing in-shoe 3000E F-scan® sensors to perform uphill walking task.

Figure 4.4: An older subject wearing in-shoe 3000E F-scan® sensors to perform downhill walking task.

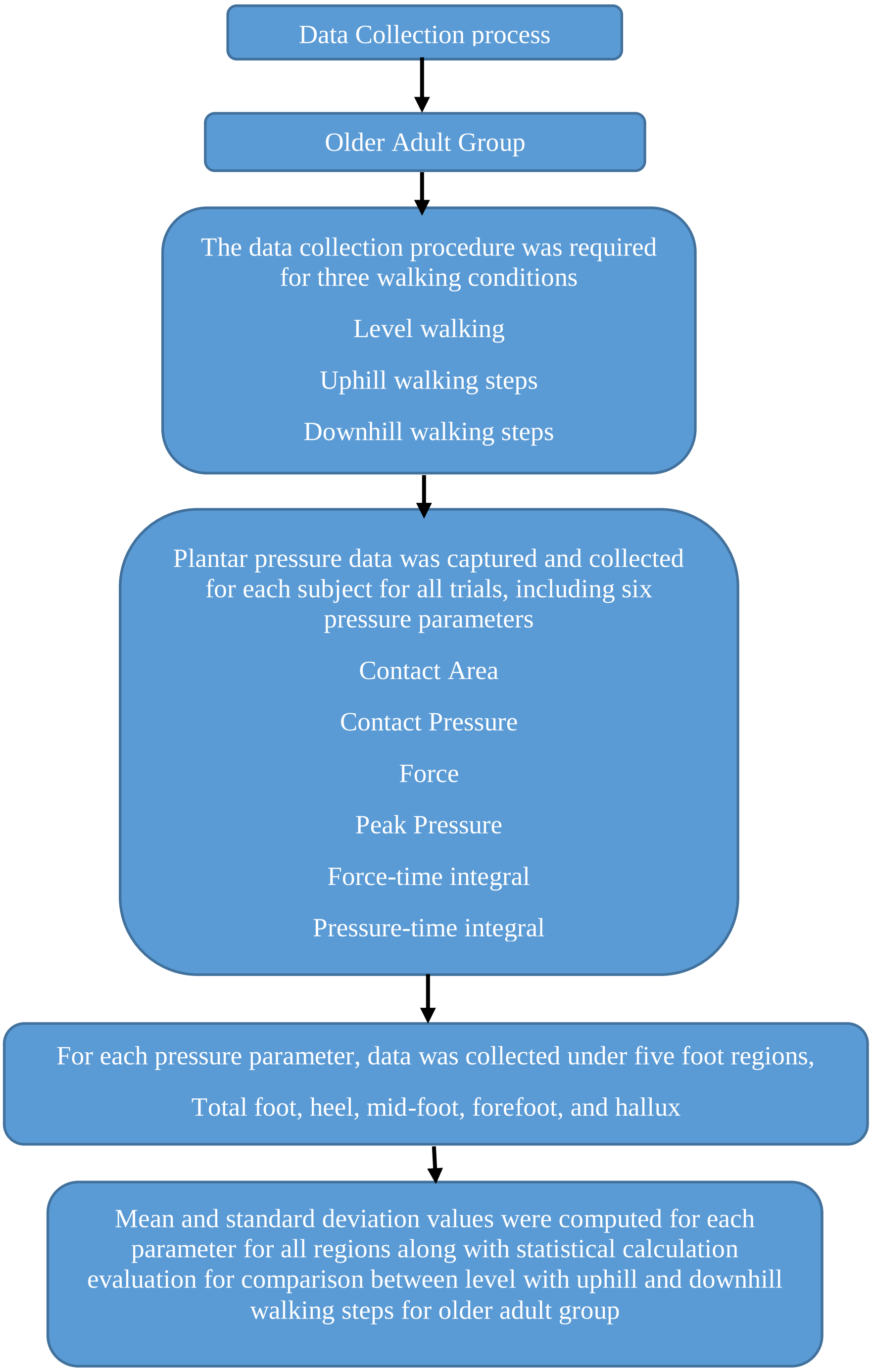

Figure 4.5: Data collection procedure used in the study for loaded gait phase comparison between level with uphill and downhill walking conditions for a group of older adult subjects.

4.4 Statistical evaluation

Intraclass correlation coefficients (ICC) were utilised to assess the reliability of the three gait test trials under the three walking conditions: level, uphill and downhill walking steps for regional plantar pressure parameters. Average measures were calculated for each walking task separately. An ICC of 0.991 indicated excellent correlation while performing level walking with the older adult group. Furthermore, an ICC of 0.982 for uphill walking steps, along with an average measure ICC of 0.965 with downhill walking steps, showed an excellent correlation, which is in very important for clinical measurements (Bautmans et al., 2011; Streiner et al., 2015). A value of 0.980 was obtained for system validity using Pearson correlation. The correlation was significant at the 0.01 level (2-tailed). IBM SPSS Statistics version 25 has been utilised to perform ICC tests and Pearson correlation test for system validity.

The experiment was designed so that the independent variables were the foot regions: the whole foot, heel, mid-foot, forefoot, and the hallux, and the three walking conditions: level walking, uphill walking steps, and the downhill walking steps task. Furthermore, the dependent variables were contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral. The control variable was the weight for each older subject, which has been used for system calibration before the gait test commencement for each subject.

The statistical differences of the contact time taken by the subjects to complete the entire stance phase of the gait cycle between level and uphill walking tasks, and again for level and downhill walking conditions were evaluated using Kolmogorov-Smirnov tests with a significance level $\alpha = 0.05$, as pointed out in Table 4.2. Additionally, the variations of plantar pressure measurements between the two gait conditions involved in the study: level and uphill walking were determined using Kolmogorov-Smirnov tests with a significance level $\alpha = 0.05$. One paired comparison: level walking relative to uphill walking steps task for each parameter, and again for each region was selected in the current work. The differences between the two above mentioned walking conditions for the plantar pressure measurements for all selected regions with a significance level $\alpha = 0.05$ have P-values as shown in Table 4.15. After which, the differences of plantar pressure patterns between the two gait tasks: level and downhill walking steps were determined using Kolmogorov-Smirnov tests with a significance level $\alpha = 0.05$. The comparisons were implemented for level walking in relation to downhill walking steps tasks for each plantar parameter: contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral, and for each plantar region: whole foot, heel, mid-foot, forefoot, and the hallux. The P-values of the comparison between level and downhill walking conditions, showing the differences of plantar pressure parameters for twenty older adults, are pointed out in Table 4.16. The statistical tests were performed on a desktop computer with the following features: Intel (R) Core 7 CPU and RAM of 8.0 GB. The model was coded in MATLab.

4.5 Foot region characteristics of level with uphill and downhill walking results

The results pointed out statistically significant variations in the contact area parameter for the whole foot, heel, and forefoot regions for the older adults group between their level and uphill walking throughout the whole stance phase of the gait cycle. Noticeably, uphill walking performed by participants decreased the mean contact area readings significantly in the above mentioned areas with (P-value < 0.05), having average contact area value of the three gait trials for the whole foot region for older adults of their level and uphill walking of (127.5 ± 21.19, 108.04 ± 17.32 cm^2), respectively. The mean contact area values at the heel and forefoot areas for level and uphill walking were (heel: 40.49 ± 5.9, 32.86 ± 5.23 cm^2), (forefoot: 65.02 ± 9.74, 61.05 ± 7.57 cm^2), respectively. It is worth noting that there was no statistically significant difference between the two walking cases undertaken by this age group in the mid-foot and hallux areas; however, uphill walking had lower mean contact area values in these two regions with mean difference of (7.053, 0.5 cm^2), respectively. Mean and standard deviation ranges for selected regions under the two walking conditions are presented in Table 4.3 along with the graph of comparison of the contact area parameter between level and uphill walking depicted in Figure 4.6.

The uphill walking significantly decreased the amount of contact pressure distributed under the heel region in comparison to that of level walking with values of (172.32 ± 66.46, 218.58 ± 57.8 kpa), respectively. In contrast, the uphill walking performed by older adults significantly increased the contact pressure measures underneath the forefoot and hallux regions when compared to their level walking with (P-value < 0.05). The mean contact pressure for older adult subjects of level and uphill walking for these two regions was (forefoot: 215.08 ± 63.77, 289.33 ± 119.68 kpa), (hallux: 158.32 ± 62.61, 200.23 ± 46.68 kpa), respectively. Regarding the mid-foot area, there was no statistical difference between the two walking conditions; however, the uphill walking had the bigger value of the contact pressure, higher than the other walking condition as shown in Table 4.4. The comparison of contact pressure recordings, showing the two walking conditions: level and uphill walking has been presented in Figure 4.7.

The results revealed a significant decrease of the force readings under the heel region while performed uphill walking for older adult subjects when compared to their level walking with (P-value < 0.05) for which the mean force recordings were (79.86 ± 20.17, 52.77 ± 15.44 kg) for the two walking conditions: level and uphill walking, respectively. The mean force values with their standard deviations for the two adopted gait trial tasks performed by older adult participants have been pointed out in Table 4.5. The comparison graph of the force measures between the above two walking cases appears in Figure 4.8.

Generally, the whole foot and forefoot had the largest values of the peak pressure for the two walking conditions undertaken by older adult individuals with in-shoe F-scan pressure sensors among the selected regions in the study. This value was followed by the hallux region, and then the heel area. The findings recorded the smallest peak pressure measures in the mid-foot area. The average outcomes of the three recorded gait cycle trials revealed that uphill walking conducted by older adults had an impact on peak pressure values measured under the five selected foot regions, pointing out a significant alteration underneath the whole foot, forefoot, and the hallux regions with (P-value < 0.05), as shown in Table 4.6. The mean peak pressure values for level walking under the whole foot, forefoot, and the hallux were (717.12 ± 269.12, 713.35 ± 273.09, 391.57 ± 266.13 kpa), respectively whereas these values for uphill walking were (914.48 ± 276.56, 914.53 ± 285.14, 596.12 ± 268.49 kpa), for the above mentioned regions, respectively. It is worth noting that the mean peak pressure values under the heel area recorded the smallest measures with no significant change during the uphill walking relative to normal level walking with mean difference of 86.6 kpa, as displayed in Figure 4.9.

The force-time integral measures were generally higher while performing uphill walking for older adult participants under selected plantar regions compared with their level walking; however, the mid-foot area had lower force-time integral value for uphill walking relative to walking on a level surface, as presented in Table 4.7. Additionally, the maximum mean force-time integral value was located under the whole foot with 81.72 ± 17.73 kg*sec, followed by the forefoot region by 53.13 ± 18.75 kg*sec, and then the heel area with 26.09 ± 10.31 kg*sec for uphill walking condition. In contrast, the results of the latter walking condition revealed lowest force-time integral values, which were located under the hallux and mid-foot regions (5.39 ± 2.85, 3.63 ± 4.33 kg*sec), respectively. The maximum variations between the two walking conditions were recorded beneath the whole foot, forefoot, and hallux regions, increasing force-time integral values significantly with (P-value < 0.05) for uphill walking to that of normal level walking while wearing in-shoe pressure sensors with mean difference of (-26.51, -22.45, -2.82 kg*sec), for the three above mentioned regions, respectively. Figure 4.10 shows the force-time integral comparison between level and uphill walking conditions performed by a number of older adult subjects.

The outcomes of uphill walking conducted by older adult participants showed a drastic increase in pressure-time integral readings compared with their level walking. The highest mean pressure-time integral measures for the three gait uphill walking trials for the older adult group were, in descending order, under the whole foot region 156.64 ± 43.8 kpa*sec, forefoot region 138.45 ± 44.11 kpa*sec, heel area 101.51 ± 39.77 kpa*sec, hallux region 83.02 ± 41.31 kpa*sec, and the mid-foot area 50.45 ± 30.12 kpa*sec, as presented in Table 4.8. Noticeably, the above mentioned integral values recorded statistically significant variations in foot loading patterns while performing uphill walking compared with the level walking conditions underneath the whole foot, heel, forefoot, and hallux regions, which were observed at (P-value < 0.05). Additionally, the mean pressure-time integral readings of the three walking gait trials had a maximum difference between the two adopted walking conditions at both forefoot and hallux regions, recording approximately double integral values for uphill walking when compared to the level walking with mean difference of (-66.24, -50.6 kpa*sec), for the above two regions respectively as displayed in Figure 4.11, which points out the comparison of integral values between the two walking conditions: level and uphill walking task.

In terms of the outcomes resulted from comparing the foot region characteristics of level and downhill walking, the results pointed out statistically significant variations for contact area values observed at (P-value < 0.05) between level and downhill walking status undertaken by twenty older adult participants, wearing in-shoe pressure sensors, under five selected main foot regions, as appeared in Table 4.9. Generally, the whole foot area had the greatest mean contact area value for the two walking conditions among the selected regions adopted in the study. This reading was followed by the forefoot region, and then the heel area. The results revealed smallest contact area values in both mid-foot and hallux regions.

Statistically significant variation at (P-value < 0.05) was found between level and downhill walking under the whole foot region with mean contact area value, comprising the three gait trials conducted by each subject for each walking case, of (127.5 ± 21.19, 106.95 ± 15.3 cm^2) for level and downhill walking, respectively. Furthermore, there was a statistical significant difference (P-value < 0.05) at both heel and mid-foot regions in which the downhill walking results showed smaller contact area values than the horizontal walking on a level surface. The mean contact area measures for the heel and mid-foot regions were (heel: 40.49 ± 5.9, 34.75 ± 6.68 cm^2), (mid-foot: 22.52 ± 13.01, 15.23 ± 9.76 cm^2) for level and downhill walking, respectively. In addition, it was found that there was a statistically significant change with (P-value < 0.05) under the forefoot region between level and downhill walking for which the contact area reading was (65.02 ± 9.74, 58.98 ± 11.48 cm^2), respectively. Thus, all contact area values were smaller with the downhill walking compared to the level walking under the five selected plantar regions; however, it is worth noting that there was no statistically significant difference in the hallux region between the two walking conditions: level and downhill walking. The comparison values between the two walking conditions undertaken by twenty older adults for mean contact area values along with the standard deviation ranges beneath all selected regions are displayed in Figure 4.12.

The mean contact pressure values were shown slightly smaller readings under the whole foot region 209.13 ± 61 kpa, heel area 214.27 ± 77.06 kpa, mid-foot region 88.97 ± 31.71 kpa, and forefoot region 208.33 ± 74.32 kpa, for downhill walking compared to level walking, performed by a group of older adults, as presented in Table 4.10. In contrast, the decrease in the above mentioned regions while walking downhill was accompanied by a significant increase with (P-value < 0.05) of mean contact pressure under the hallux region compared with walking on a level surface. The mean contact pressure under the hallux area during both level and downhill walking was (158.32 ± 62.61, 250.02 ± 124.08 kpa), respectively, as appeared in Figure 4.13.

Additionally, the average results of the three recorded gait trials performed by older adult participants during downhill walking conditions revealed that there was a slight reduction of the mean force values under the whole foot, heel, mid-foot, and forefoot regions compared to level walking status for which the mean difference of the force values between level and downhill walking conditions was (0.89, 14.84, 5.11, 8.03 kg) for the above four mentioned regions, respectively, and that has been pointed out in Table 4.11. However, the force value was increased significantly (P-value < 0.05) while older adult subjects were walking on a downhill surface under the hallux region compared to that of horizontal walking on a level surface. The mean force value under the hallux region for level and downhill walking status recorded (15.83 ± 8.4, 25.24 ± 13.09 kg), respectively, as displayed in Figure 4.14.

The highest peak plantar pressure reading, for both adopted walking conditions: level and downhill walking, undertaken by a number of older adult participants, was recorded under the whole foot and forefoot regions, followed by the hallux and heel regions whereas the lowest value amongst the selected foot regions was found under the mid-foot region for both the above two gait tasks. The results revealed a consistent increase in the foot loading distribution patterns for peak pressure readings for the downhill walking relative to the level walking, specifically for the whole foot, forefoot, and hallux regions.

Additionally, there was a statistically significant variation in peak pressure measures between the two walking conditions, which have been observed under the above three mentioned foot regions at (P-value < 0.05). However, the results showed no significant change under the heel and mid-foot regions. The greatest difference of the mean peak pressure measures between level and downhill walking was found under the whole foot, forefoot, and hallux regions. The mean peak pressure readings in the whole foot and forefoot regions for level walking were (717.12 ± 269.12, 713.35 ± 273.09 kpa), respectively while these values were (958.03 ± 350.14, 940.18 ± 321.72 kpa), respectively for the downhill walking condition. Furthermore, the mean value of the peak pressure variable in the downhill walking status was approximately twice than that of the level walking under the hallux region for which the mean peak pressure reading was (391.57 ± 266.13, 666.37 ± 426.24 kpa), for level and downhill gait respectively, as shown in Table 4.12. It is worth noting that the results showed close peak pressure values, which were recorded under the heel and mid-foot regions for the two walking conditions with mean differences of (2.4, 8.93 kpa), for the two above regions respectively. The comparison, between level and downhill walking of foot loading data for the means of peak pressure along with the standard deviation values under selected foot regions for a number of older adult individuals, is depicted in Figure 4.15.

Generally, there were differences of foot characteristics in the measured parameter of force-time integrals between the two walking conditions: level and downhill status, recording a bigger value for downhill walking than that of level walking performed by a group of older adults under all selected foot regions in the study. Obviously, there was a substantial increase in force-time integral readings, which were located beneath the whole foot, forefoot, and hallux regions resulting from performing the downhill walking, showing a statistically significant difference, which was observed at (P-value < 0.05) in comparison with normal walking on a level surface. The mean force-time integral for a downhill walking task underneath the whole foot, forefoot, and hallux regions recorded (82.95 ± 22.15, 54.69 ± 20.86, 12.06 ± 10.36 kg*sec), respectively while these values for the level walking were (55.21 ± 9.73, 30.67 ± 6.81, 2.57 ± 1.72 kg*sec), for the above three regions respectively, as presented in Table 4.13. Furthermore, the value of force-time integral under the heel and mid-foot areas recorded higher measures while the older adult participants were under downhill conditions compared with their level walking, the outcomes revealed an increase in the force-time integral readings by mean difference of (-8.9, -0.81 kg*sec), between level and downhill walking for the two mentioned regions respectively. The average force-time integral results of the three recorded gait trials under selected foot regions to compare the outcomes for a group of twenty older adult subjects under the two adopted walking tasks are exhibited in Figure 4.16.

The mean pressure-time integral values for both walking conditions: level and downhill walking performed by a number of older adult participants are presented in Table 4.14. The highest mean value of the pressure-time integral within the level walking condition was recorded under the region of the whole foot 103.29 ± 24.91 kpa*sec, followed by the forefoot region 72.2 ± 15.57 kpa*sec, and then the heel area by mean measure of 67.75 ± 16.98 kpa*sec. Finally, the lowest mean readings of the pressure-time integral for the level walking status were located at both mid-foot and hallux regions, pointing out close values of (34.65 ± 12.06, 32.42 ± 17.29 kpa*sec), for the above two mentioned regions respectively. Additionally, the highest mean values of the pressure-time integral variable measured for downhill walking task were, in descending order, beneath the whole foot region 156.5 ± 45.27 kpa*sec, hallux region 142.55 ± 90.35 kpa*sec, forefoot region 127.54 ± 34.97 kpa*sec, heel area 109.92 ± 52.24 kpa*sec, and under the mid-foot area 51.7 ± 28.68 kpa*sec. Figure 4.17 depicts the foot loading data of pressure-time integral comparison between the two walking conditions which have been adopted in this study. Apparently, there was a statistically significant difference with (P-value < 0.05) in foot characteristics, the pressure-time integral values, between the two walking functional tasks: level and downhill walking performed by a group of older adult individuals. The mean pressure-time integral, of the three recorded gait trials for each walking condition performed by each subject while wearing pressure sensor insoles, for reading the downhill walking conditions was significantly higher than that of the level walking condition under the whole foot and heel regions. Furthermore, the comparison results revealed statistically a significant variation between the two walking tasks, pointing out an excessive increase of the mean pressure-time integral for downhill walking when compared to walking on a level surface under the forefoot region, particularly beneath the hallux area, which displayed a substantial increase in integral readings within the downhill walking status. It is worth noting that the mid-foot region for the downhill gait case recorded a higher reading in the mean pressure-time integral measures than that for the level walking status with no mentioned significant difference.

The differences between the two adopted walking cases: level and uphill walking for the plantar pressure parameters for all regions selected in the study with a significance level $\alpha = 0.05$ have P-values as shown in Table 4.15. Furthermore, the differences between the two adopted walking conditions: level and downhill gait for the plantar pressure parameters for all regions selected in the study with a significance level $\alpha = 0.05$ have P-values as shown in Table 4.16.

Table 4.3: Mean values and standard deviations for contact area in (cm^2) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

Contact Area	**Level walking**		**Uphill walking**	
	Mean	SD	Mean	SD
Whole foot	127.50	21.19	108.04	17.32
Heel	40.49	5.90	32.86	5.23
Mid-foot	22.52	13.01	15.46	11.42
Forefoot	65.02	9.74	61.05	7.57
Hallux	10.34	2.76	9.84	2.28

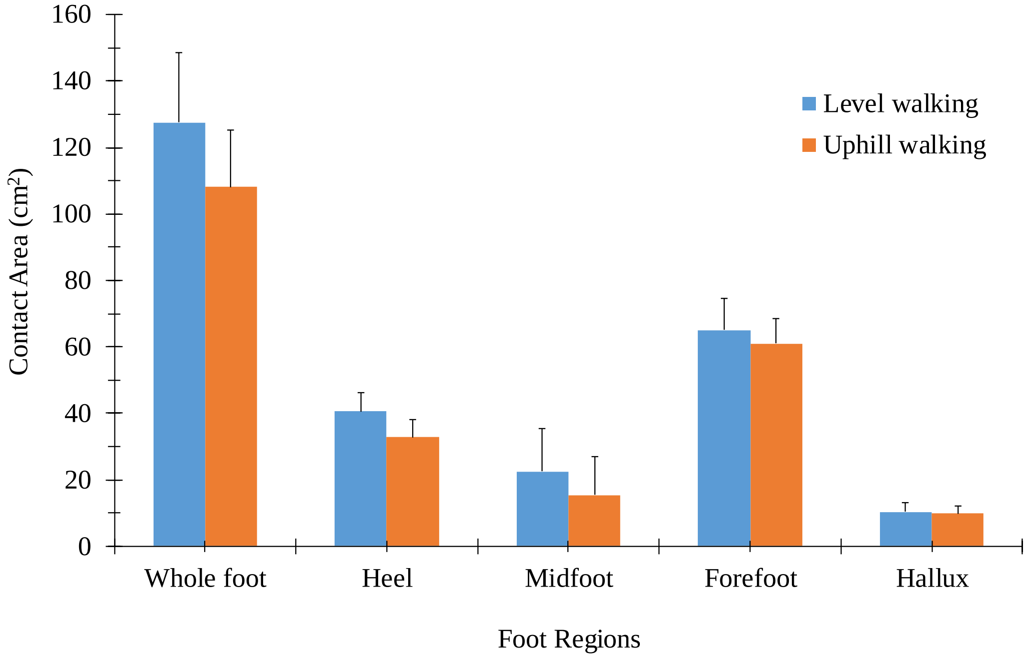

Figure 4.6: Mean and standard deviation of contact area values in (cm^2) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.4: Mean values and standard deviations for contact pressure in (kpa) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

Contact Pressure	**Level walking**		**Uphill walking**	
	Mean	SD	Mean	SD
Whole foot	215.50	61.46	238.85	60.91
Heel	218.58	57.80	172.32	66.46
Mid-foot	96.30	39.19	107.58	132.02
Forefoot	215.08	63.77	289.33	119.68
Hallux	158.32	62.61	200.23	46.68

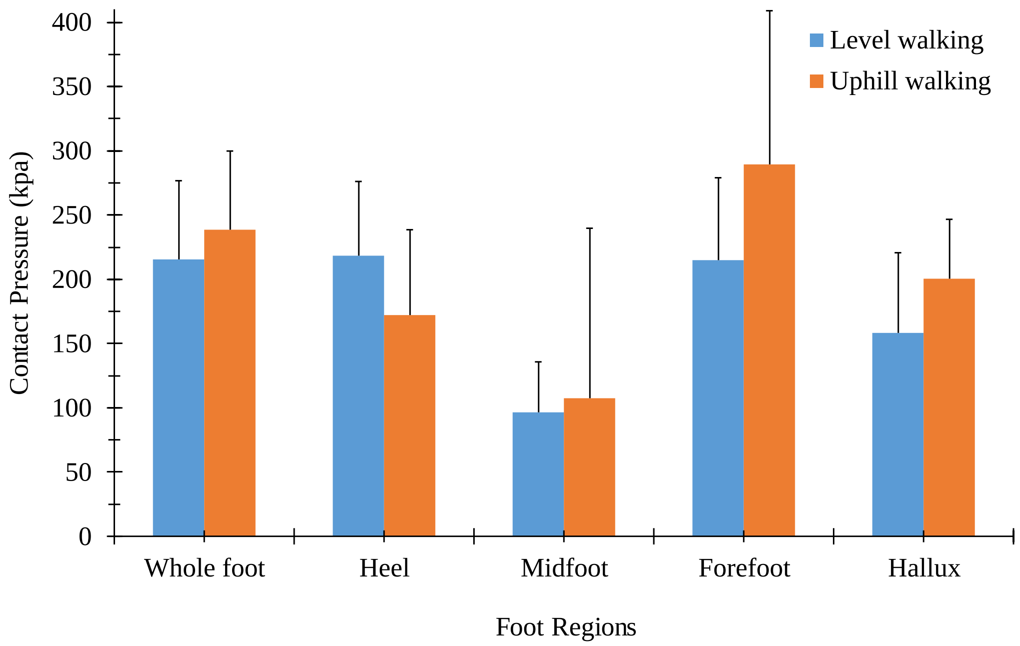

Figure 4.7: Mean and standard deviation of contact pressure values in (kpa) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.5: Mean values and standard deviations for the force in (kg) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

Force	**Level walking**		**Uphill walking**	
	Mean	SD	Mean	SD
Whole foot	114.49	19.46	106.65	16.57
Heel	79.86	20.17	52.77	15.44
Mid-foot	14.95	14.16	8.63	7.90
Forefoot	112.47	21.46	100.01	22.70
Hallux	15.83	8.40	14.97	7.56

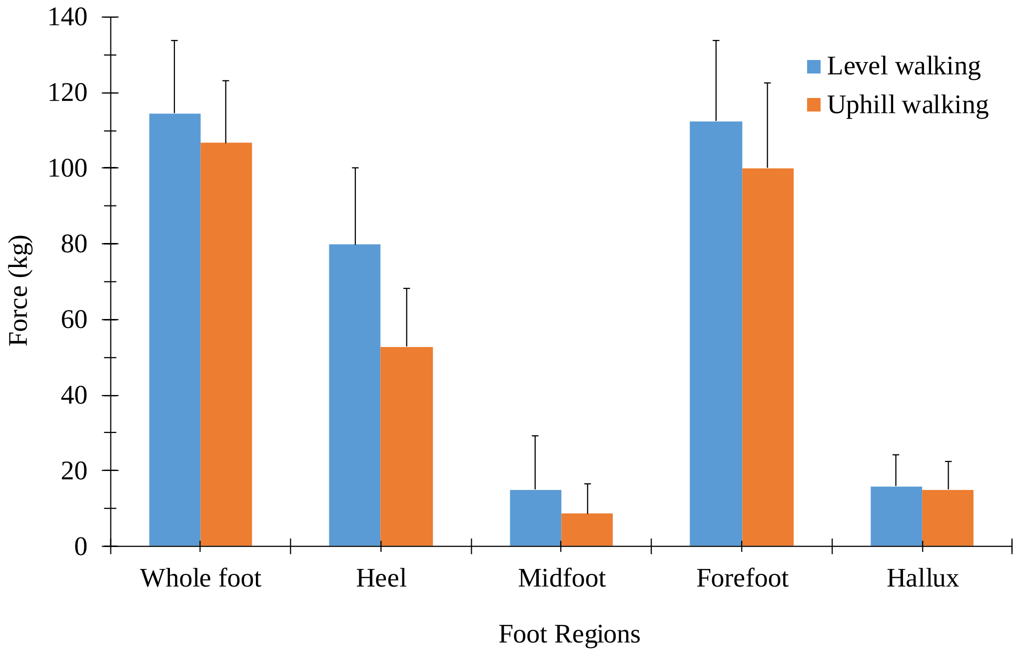

Figure 4.8: Mean and standard deviation of force values in (kg) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.6: Mean values and standard deviations for peak pressure in (kpa) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

Peak Pressure	**Level walking**		**Uphill walking**	
	Mean	SD	Mean	SD
Whole foot	717.12	269.12	914.48	276.56
Heel	477.88	158.87	391.28	154.16
Mid-foot	148.80	78.44	144.08	140.64
Forefoot	713.35	273.09	914.53	285.14
Hallux	391.57	266.13	596.12	268.49

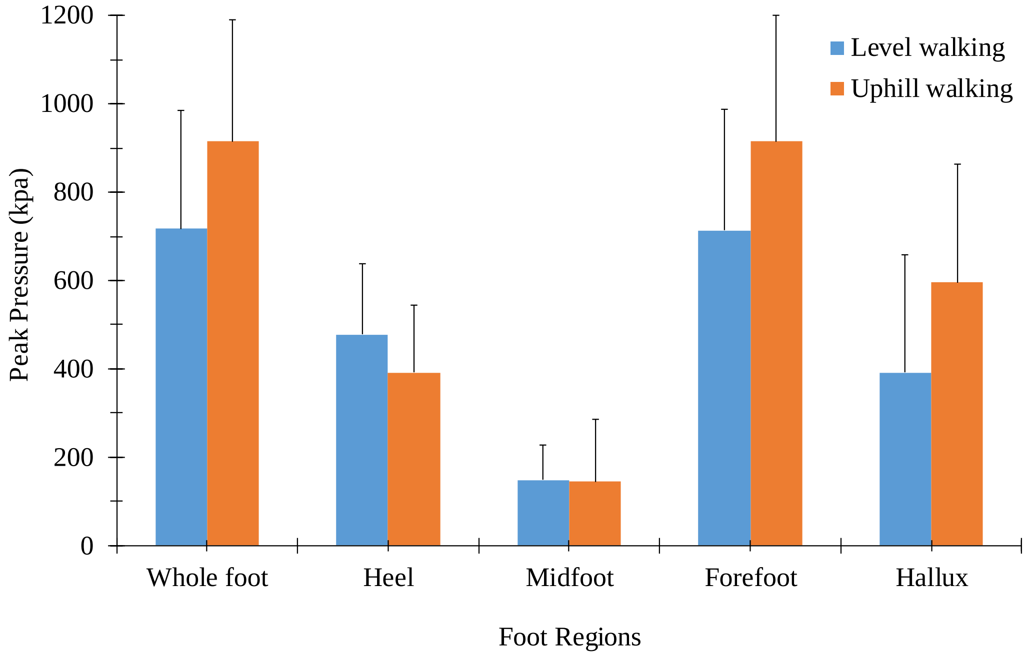

Figure 4.9: Mean and standard deviation of peak pressure values in (kpa) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.7: Mean values and standard deviations for force-time integral (FTI) in (kg*sec) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

FTI	**Level walking**		**Uphill walking**	
	Mean	SD	Mean	SD
Whole foot	55.21	9.73	81.72	17.73
Heel	20.74	6.39	26.09	10.31
Mid-foot	4.15	4.17	3.63	4.33
Forefoot	30.67	6.81	53.13	18.75
Hallux	2.57	1.72	5.39	2.85

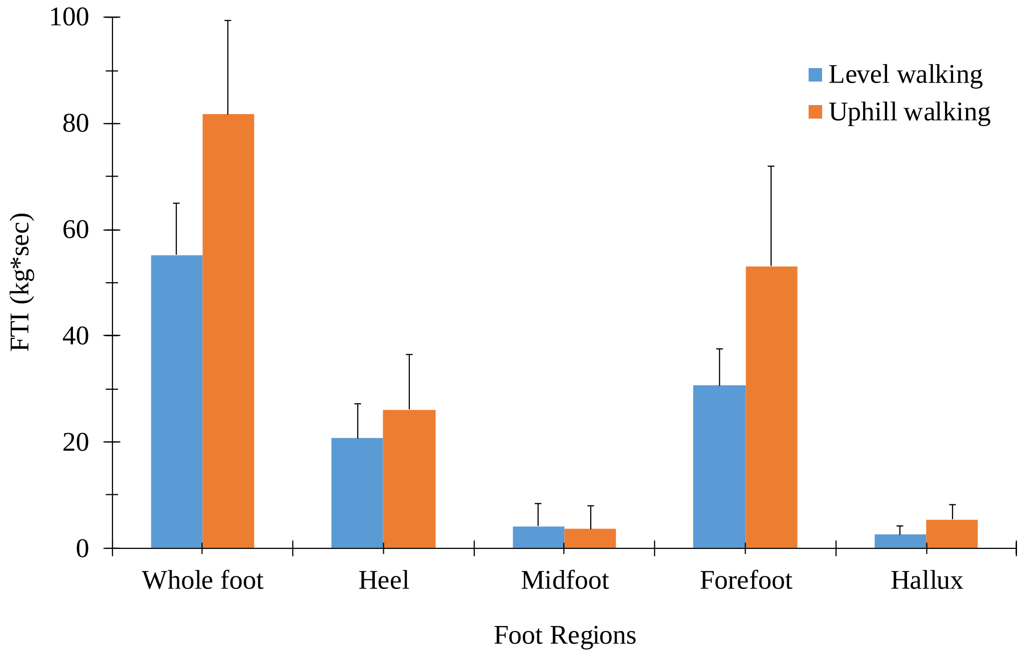

Figure 4.10: Mean and standard deviation of force-time integral values in (kg*sec) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.8: Mean values and standard deviations for pressure-time integral (PTI) in (kpa*sec) for older adults of level and uphill walking of three walking trials for each subject in five selected regions.

PTI	Level walking		Uphill walking	
	Mean	SD	Mean	SD
Whole foot	103.29	24.91	156.64	43.80
Heel	67.75	16.98	101.51	39.77
Mid-foot	34.65	12.06	50.45	30.12
Forefoot	72.20	15.57	138.45	44.11
Hallux	32.42	17.29	83.02	41.31

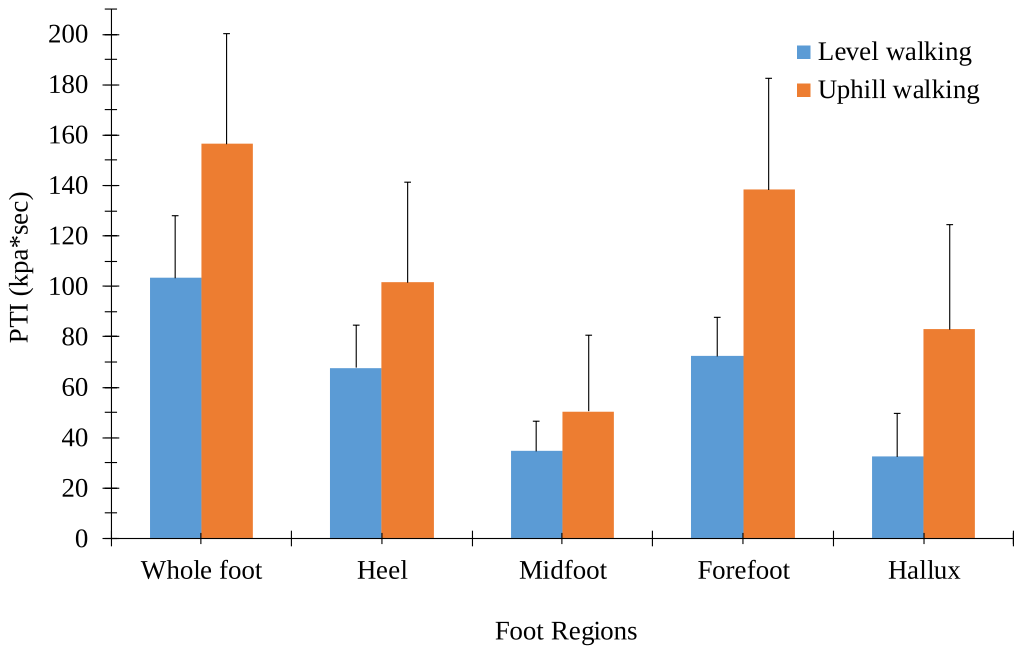

Figure 4.11: Mean and standard deviation of pressure-time integral values in (kpa*sec) for comparison conducted between level and uphill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.9: Mean values and standard deviations for contact area in (cm^2) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

Contact Area	Level walking		Downhill walking	
	Mean	SD	Mean	SD
Whole foot	127.50	21.19	106.95	15.30
Heel	40.49	5.90	34.75	6.68
Mid-foot	22.52	13.01	15.23	9.76
Forefoot	65.02	9.74	58.98	11.48
Hallux	10.34	2.76	9.82	3.12

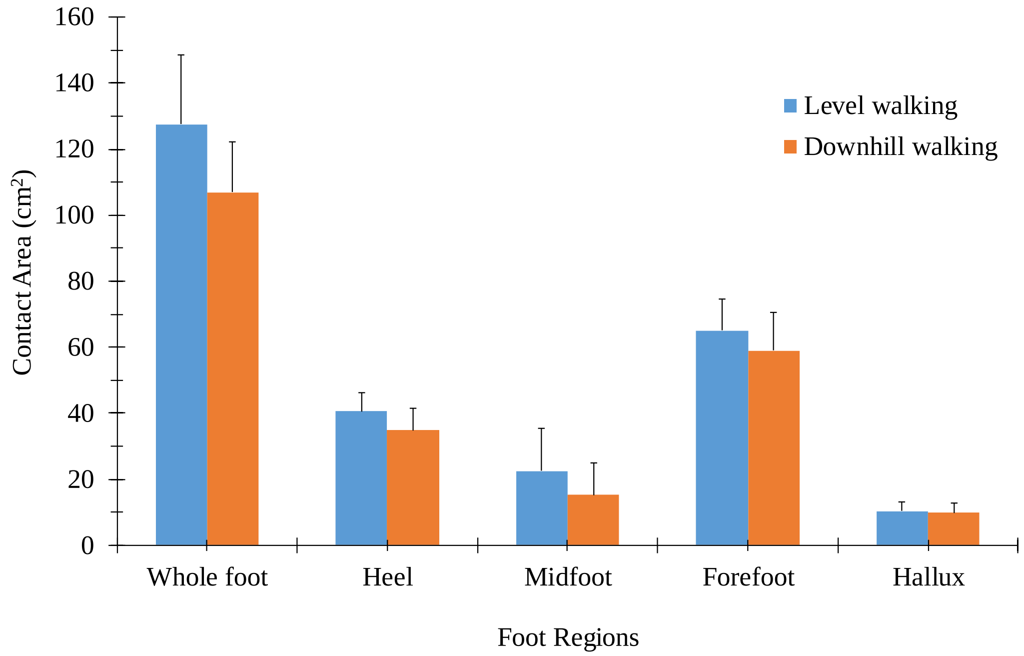

Figure 4.12: Mean and standard deviation of contact area values in (cm^2) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.10: Mean values and standard deviations for contact pressure in (kpa) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

Contact Pressure	**Level walking**		**Downhill walking**	
	Mean	SD	Mean	SD
Whole foot	215.50	61.46	209.13	61.00
Heel	218.58	57.80	214.27	77.06
Mid-foot	96.30	39.19	88.97	31.71
Forefoot	215.08	63.77	208.33	74.32
Hallux	158.32	62.61	250.02	124.08

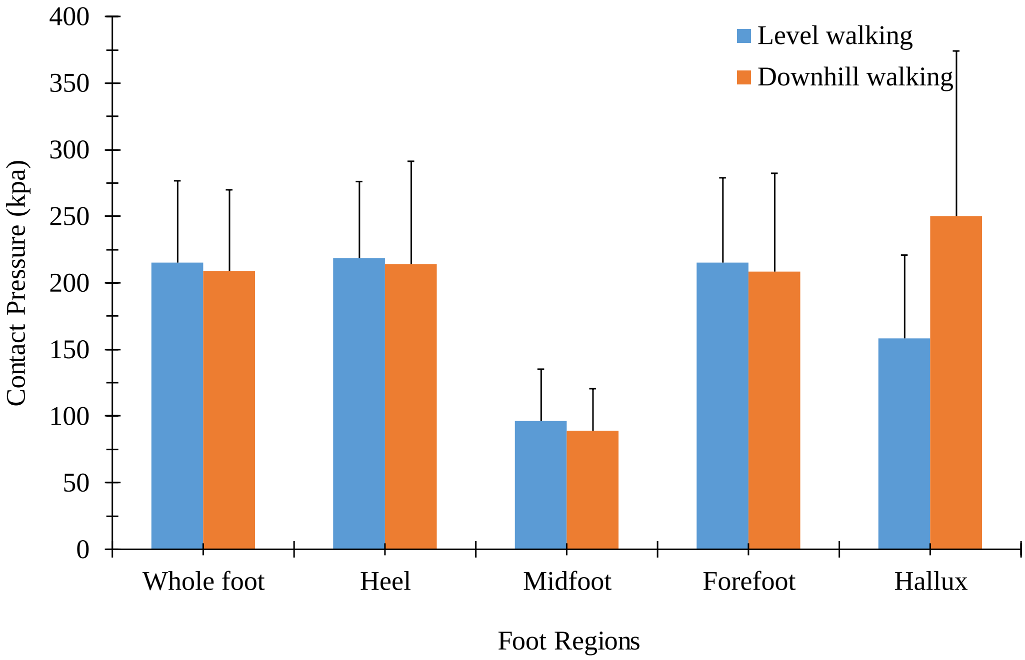

Figure 4.13: Mean and standard deviation of contact pressure values in (kpa) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.11: Mean values and standard deviations for the force in (kg) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

Force	Level walking		Downhill walking	
	Mean	SD	Mean	SD
Whole foot	114.49	19.46	113.60	22.53
Heel	79.86	20.17	65.01	18.31
Mid-foot	14.95	14.16	9.85	8.56
Forefoot	112.47	21.46	104.45	32.84
Hallux	15.83	8.40	25.24	13.09

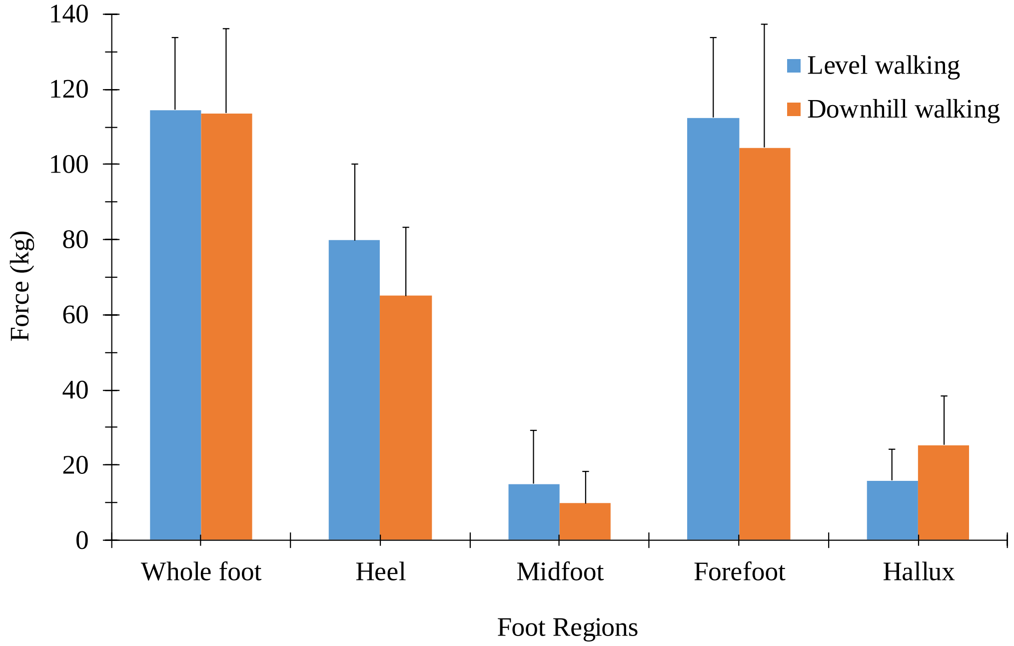

Figure 4.14: Mean and standard deviation of force values in (kg) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.12: Mean values and standard deviations for peak pressure in (kpa) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

Peak Pressure	**Level walking**		**Downhill walking**	
	Mean	SD	Mean	SD
Whole foot	717.12	269.12	958.03	350.14
Heel	477.88	158.87	475.48	194.92
Mid-foot	148.80	78.44	139.87	68.82
Forefoot	713.35	273.09	940.18	321.72
Hallux	391.57	266.13	666.37	426.24

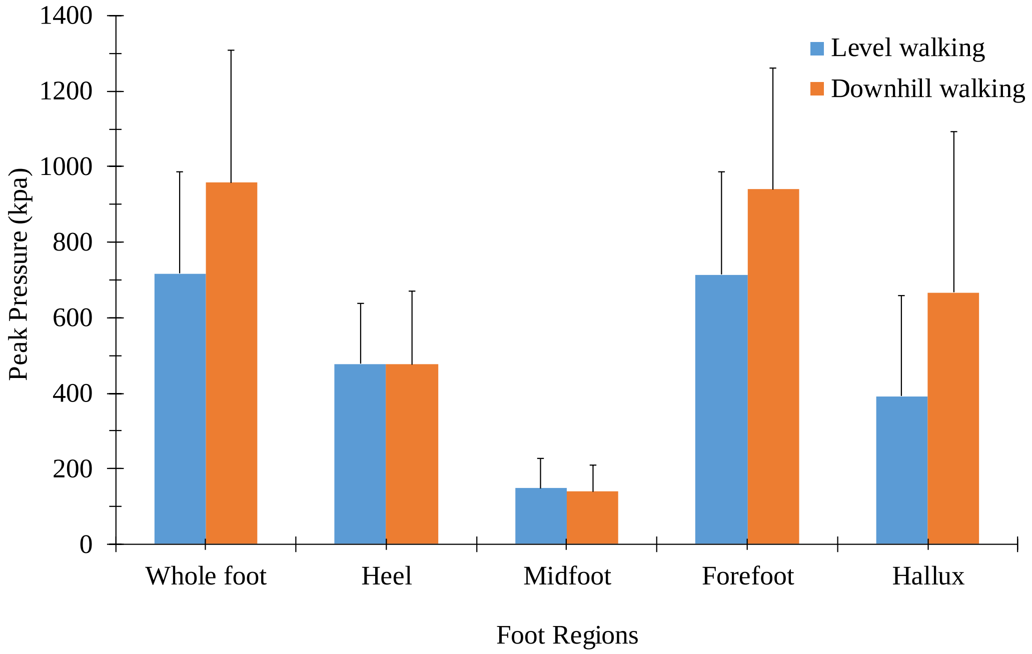

Figure 4.15: Mean and standard deviation of peak pressure values in (kpa) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.13: Mean values and standard deviations for force-time integral (FTI) in (kg*sec) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

FTI	Level walking		Downhill walking	
	Mean	SD	Mean	SD
Whole foot	55.21	9.73	82.95	22.15
Heel	20.74	6.39	29.64	18.10
Mid-foot	4.15	4.17	4.96	6.25
Forefoot	30.67	6.81	54.69	20.86
Hallux	2.57	1.72	12.06	10.36

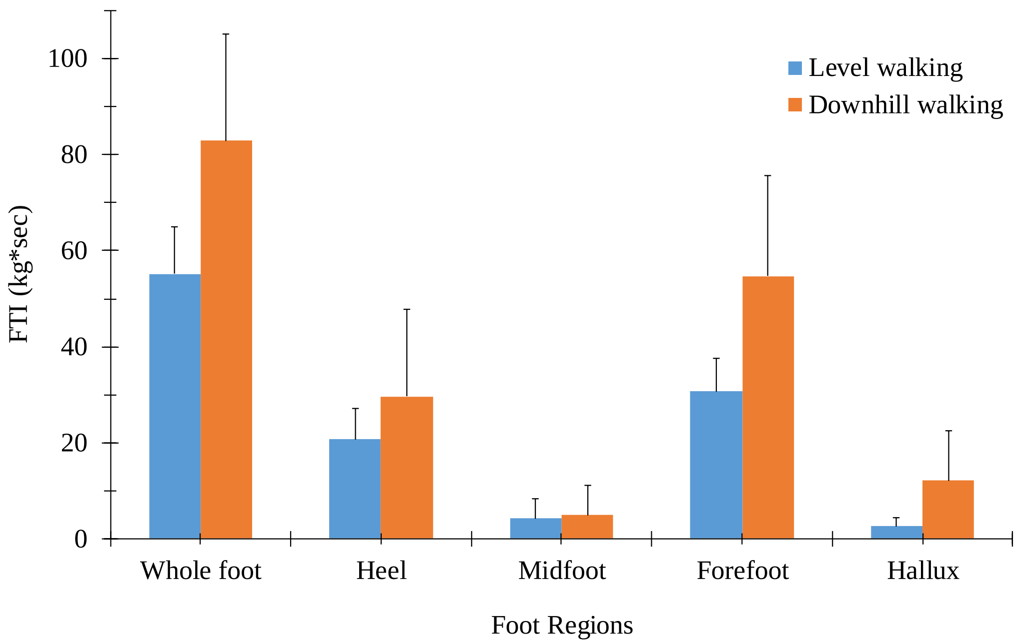

Figure 4.16: Mean and standard deviation of force-time integral values in (kg*sec) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.14: Mean values and standard deviations for pressure-time integral (PTI) in (kpa*sec) for older adults of level and downhill walking of three walking trials for each subject in five selected regions.

PTI	Level walking		Downhill walking	
	Mean	SD	Mean	SD
Whole foot	103.29	24.91	156.50	45.27
Heel	67.75	16.98	109.92	52.24
Mid-foot	34.65	12.06	51.70	28.68
Forefoot	72.20	15.57	127.54	34.97
Hallux	32.42	17.29	142.55	90.35

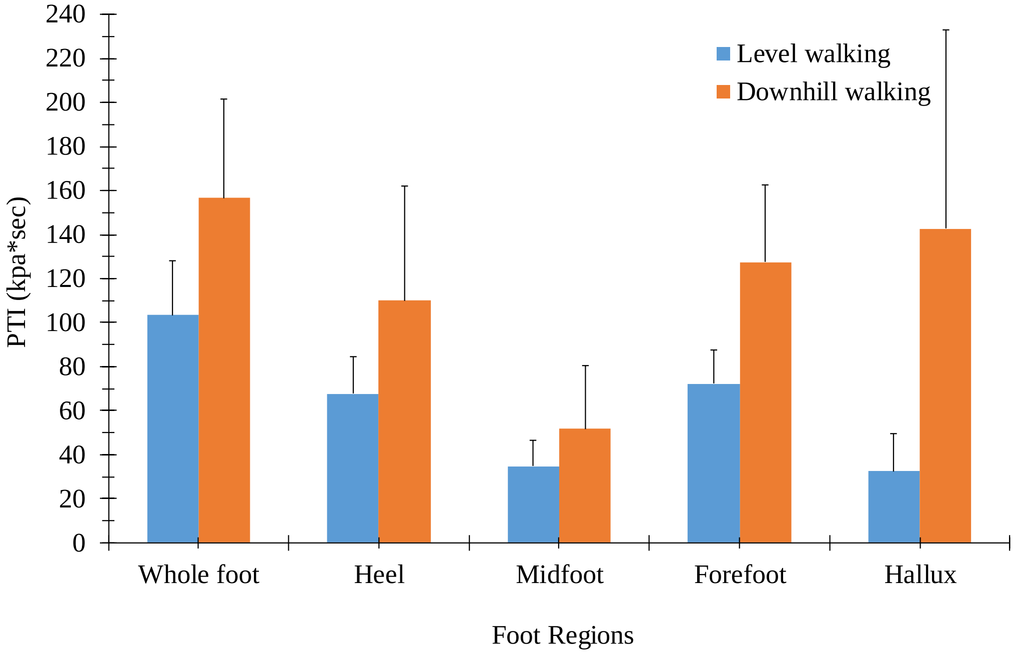

Figure 4.17: Mean and standard deviation of pressure-time integral values in (kpa*sec) for comparison conducted between level and downhill walking for older adults of three walking trials for each subject in five selected plantar regions during the whole stance phase.

Table 4.15: Kolmogorov-Smirnov test P-values for the plantar pressure measurement comparison between level and uphill walking for twenty older adults under five selected plantar regions with a significance level α = 0.05.

	Whole foot	**Heel**	**Mid-foot**	**Forefoot**	**Hallux**
Contact Area (cm^2)	0.0082	7.2529e-04	0.2753	0.050	0.7710
Contact Pressure (kpa)	0.2753	0.0232	0.7710	0.0082	0.050
Force (kg)	0.4973	1.8331e-04	0.2753	0.2753	0.4973
Peak Pressure (kpa)	0.0082	0.1349	0.4973	0.0026	0.0082
FTI (kg*sec)	4.1505e-05	0.2753	0.7710	8.4181e-06	0.0026
PTI (kpa*sec)	7.2529e-04	0.0026	0.1349	2.4894e-07	1.8331e-04

Table 4.16: Kolmogorov-Smirnov test P-values for the plantar pressure measurement comparison between level and downhill walking for twenty older adults under five selected plantar regions with a significance level α = 0.05.

	Whole foot	**Heel**	**Mid-foot**	**Forefoot**	**Hallux**
Contact Area (cm^2)	0.0026	0.0232	0.050	0.0026	0.7710
Contact Pressure (kpa)	0.9655	0.7710	0.9655	0.7710	0.0082
Force (kg)	0.7710	0.1349	0.4973	0.2753	0.050
Peak Pressure (kpa)	0.0491	0.9999	0.7710	0.0491	0.0491
FTI (kg*sec)	1.8331e-04	0.2753	0.7710	2.4894e-07	1.5295e-06
PTI (kpa*sec)	0.0026	0.0082	0.1349	2.4894e-07	2.4894e-07

4.6 Discussion

Mobility and walking performance are likely to be impaired with advancing age, leading to increased mortality among this age stage (Menz et al., 2018; Ortega et al., 2015; Studenski et al., 2011). Studies have shown that within older adult population, aged over 65 years, more than 30% of that population fall approximately once a year

(Control et al., 2006; Hong et al., 2015). It has been shown that the risk of falling encountered by elderly people can be increased with increasing challenges required to balance the control during walking on stairs and slope surfaces, particularly while upstairs and uphill walking (Honeycutt et al., 2002; Hong et al., 2015). Maintaining the balance during walking is a challenge for human systems of postural control due to the fact that posture control and balance are both substantial mechanisms for human locomotion (Dimitrijevic et al., 1981; Vieira et al., 2017; Winter, 1995b). Balance control degeneration and muscle strength loss have proved to be the reasons behind observed human gait changes with advancing age (Winter et al., 1990). Outdoor daily walking involves changes in surface elevation, demanding body adjustment, particularly for uphill and downhill walking steps, which requires an adaptation of the biomechanics of walking compared to that required in level walking (Gottschall et al., 2011; Item-Glatthorn et al., 2016; Kimel-Naor et al., 2017; McIntosh et al., 2006; Vieira et al., 2017). Outdoor walking surfaces can include footpath inclination and the ramps made to facilitate building access and others (Vieira et al., 2017).

Gait parameters have been shown to vary relative to the surface slope (Crowe et al., 1996; Kawamura et al., 1991; Kimel-Naor et al., 2017; Sun et al., 1996). As we have mentioned, with age-related factors such as muscle strength degeneration and range of joint motion limitation, older adults may suffer more in maintaining the balance necessary while walking on inclined surfaces. Furthermore, as it has been shown that walking on inclined ramps can diminish gait stability and change gait variability (Vieira et al., 2017), thus increasing the risk of falling within this age group (Hong et al., 2015; Prince et al., 1997). Therefore, the study suggested involving walking on inclined surfaces by older adult participants through a comparison with the gait parameters of their level walking, thereby having a baseline data from the study outcomes is essential for future clinical domains in either treating or adopting special clinical interventions to avoid developing foot conditions sustained with advancing age. Additionally, the study outcomes may also be significant for shoe manufacturers in terms of designing optimal shoe insoles, which may assist to reduce the irritation accompanied with various functional activities for older adults.

The objective of this study was to examine the effect of adopting various walking conditions: level, uphill, and downhill walking, which have been performed by twenty older adult subjects, on the plantar pressure characteristics under specific plantar regions, namely whole foot, heel, mid-foot, forefoot, and hallux. In order to thoroughly study the influence of each walking condition while wearing 3000E F-scan insole sensors under all anatomical foot regions specified in the study, a number of plantar parameters: contact area, contact pressure, force, peak pressure, force-time integral, and pressure-time integral, have been utilised to measure the difference in the readings under various walking tasks performed via subjects of older age. Firstly, the study examined the uphill walking status relative to horizontal walking on a level surface. Studies have shown that uphill walking demands more of a challenge than that of level walking (Hong et al., 2014; Hong et al., 2015; Lay et al., 2006; Leroux et al., 2002; Sheehan and Gottschall, 2012) as the two limbs must work together to make certain of preserving the stabilization and the body progression, particularly for elderly people. Additionally, as we have mentioned that maintaining balance control during uphill walking tasks for older people is more difficult compared to the normal walking due to age-related degeneration, which may increase the risk of falling experienced by this age group (Hong et al., 2015; Ortega and Farley, 2015). The risk of falling faced by elderly people was found to be at greater level for uphill walking even when compared with walking up stairs (Hong et al., 2015; Sheehan and Gottschall, 2012).

Previous studies for uphill walking conditions have been mostly concentrated on young adult subjects utilising different measurement systems for different method requirements, which have been pointed out in the background section provided in this chapter. To our knowledge, for this age group of healthy older adults, there is a lack of awareness in studies that include the plantar parameters. Therefore, the current study suggests a thorough examination of the alteration in plantar patterns for twenty older adults aged 65-80 years during uphill walking in relation to level walking as the uphill walking is likely to be encountered in daily activities. Thus, the findings can have useful implications for individuals of the same age group, which may be clinically significant. Being able to understand the relative alteration of level and uphill functional tasks can assist in providing a reference to create an appropriate insole pad designed based on the research outcomes. It can also help to determine whether the slope surface can be safely inclined by people from this age, or whether an appropriate speed should be chosen to achieve a sufficient confidence while doing these tasks safely.

Contact area values, measured in the current study, were lower for the uphill walking activity compared to walking in a straight line for a number of older adult participants under all selected plantar regions, particularly beneath the whole foot, heel, and forefoot regions. The result was largely in line with that conducted by Kim et al. (2013), who found lower contact area values under some of the selected foot regions, mainly beneath the medial heel, lateral heel, (third, fourth, and fifth) metatarsal head, and hallux regions during stair ascent activity compared to level walking at self-selected speeds using Tekscan as a plantar pressure measurement system.

Plantar pressure values are the distributed forces under the foot experienced during various normal daily activities. Being able to understand the influence of each walking activity on the force distribution might be essential in terms of preventing foot injuries (Wervey et al., 1997). The results revealed lower contact pressure value at the heel area for the functional task of uphill walking steps relative to that of normal level walking. The findings were consistent with previous studies undertaken by Grampp et al. (2000), Maluf et al. (2004), and in another study Ho et al. (2010). However, these studies have been performed for people with specific pathological conditions or for subjects of different age groups. For instance, the study conducted by (Maluf et al., 2004) was intended to assess the association of plantar pressure measurement of level walking with other functional activities for sixteen patients with diabetic neuropathy using in-shoe multisensory pressure sensors (IMD) as a data acquisition device. Furthermore, the aim of the research undertaken by Ho et al. (2010) was to examine the influence of different incline slopes measured during treadmill jogging on plantar pressure distribution under eight foot regions collected by the Pedar-X system for twenty healthy female adults.

In contrast, there was a remarkable main impact, while performing uphill walking by a group of older adults who participated in the current study, on dynamic plantar pressure readings under the forefoot area. The higher contact pressure measure was found under the forefoot area for uphill walking conditions when compared to the level walking status. In this research, the higher contact pressure value within the forefoot region was confirmed by previous studies conducted by Wervey et al. (1997), and Maluf et al. (2004), while the former study has been performed for stair climbing instead of ramp climbing. These studies emphasised that the pressure beneath the forefoot area is greater for uphill walking and stair climbing than the walking in a level straight line. Our findings of this investigation highlighted that the higher contact pressure values at the forefoot site under uphill walking conditions may be explained by the increase in ankle mobility and push-off force required to accomplish these tasks (Maluf et al., 2004). Despite the reduction in contact area value under the hallux region for uphill walking steps, the results kept showing higher contact pressure values in contrast to the level walking in which larger contact area with less contact pressure was distributed. This would possibly increase the risk of injuries accompanied with uphill walking tasks for older adults as elevated pressure values were found to be associated with increasing the risk of skin breakdown for diabetic patients (Frykberg et al., 1998; Maluf et al., 2004; Stess et al., 1997; Veves et al., 1992).

It has been shown from previous studies that the muscle forces of the human lower limb were altered significantly during sloped walking in relation to level walking (Alexander et al., 2016). As described previously in the results section, the uphill walking condition witnessed a significant alteration in force values corresponding to those of level walking tasks under the heel region. The finding was compatible with the studies, which stated that uphill walking demonstrated a reduction in rear foot loading (Grampp et al., 2000; Maluf et al., 2004). The reduction in force values with uphill walking compared to level walking condition may occur due to the decrease in the contact time exerted during the heel contact while performing this activity, thereby providing a stable level of balance required to achieve safe climbing up by older adult individuals participated in our study, as emphasised by previous studies (Guo et al., 2006; Ho et al., 2010).

Clinically, elevated plantar pressure values have been found to be associated with the development of foot plantar ulcers (Fawzy et al., 2014; Tang et al., 2015; Urry, 2002; Veves et al., 1992). Furthermore, it has been shown that the outcome of plantar pressure measurements revealed significant alterations between walking on inclined surfaces and walking on level surfaces (Grampp et al., 2000; Kästenbauer et al., 1995; Simpson et al., 1993; Urry, 2002). Hence, it is essential to adopt peak pressure factor when analysing plantar pressure patterns to underscore the variations between walking on level and inclined surfaces, particularly when older adult subjects are the main study concern. It has been postulated that peak pressure values during uphill walking would be lower than that during level walking due to more contact time occupied when presented with functional tasks, which require more challenges than normal walking on a straight level surface (Maluf et al., 2004). Contrary to expectation, the results revealed an excessive increase in the peak pressure readings beneath the whole foot, forefoot, and hallux regions for participants selected in the study. The increase in the peak pressure values under the forefoot and hallux sites in our own study can be attributed to the increase in muscle activation patterns required with uphill walking, with addition to greater plantar loading needed to raise the body weight during this specific task (Grampp et al., 2000; Sun et al., 1996). The increase in the above mentioned regions was accompanied by a reduction in peak pressure measures under the heel and mid-foot areas for uphill walking relative to level walking tasks. These findings were in accordance with the study conducted by Grampp et al. (2000), which aimed to evaluate the plantar loading variations during five gradient conditions using a treadmill. The Pedar® in-shoe pressure sensor insole was adopted as a measurement system to collect data for twenty adult participants. The results pointed out a reduction in peak pressure values under the heel area, whereas an increase in peak pressure values was found under the first metatarsal head, and the hallux regions. Furthermore, the findings of the current study relative to peak pressure readings were in line to some extent with the ones undertaken by Maluf et al. (2004), and Ho et al. (2010). These studies emphasised that peak pressure values were higher during uphill walking under the forefoot and hallux regions, and lower under the heel area compared to those resulting from walking on a level surface. There is a possible reason to explain the excessive increase of peak pressure values underneath the forefoot and hallux regions with uphill walking conditions. The foot may demonstrate more inversion to be able to achieve a stable level for pushing off required to eventually terminate the stance phase by people of this age (Ho et al., 2010).

The results exhibited higher force-time integral values underneath the whole foot, forefoot, and hallux regions during uphill walking compared to level walking. Additionally, variation in the mean pressure-time integral measures was noticeable, with uphill walking conditions displaying significantly higher values under the whole foot, heel, forefoot, and hallux regions. The outcome of the study undertaken by Maluf et al. (2004) corresponded to some extent with that of our study. Maluf et al. (2004) emphasised that the higher pressure-time integral was found beneath the first and third metatarsal head areas during stair climbing with the addition of increasing the pressure-time integral value at the heel area during uphill walking compared to level walking; however, the study has been performed on subjects with diabetic neuropathy. The result of this investigation was also compatible to some extent with the study conducted by Grampp et al. (2000), which observed a higher pressure-time integral under the second and third metatarsal head areas during uphill walking compared to that of the level walking condition. The excessive amount of pressure-time integral at forefoot and hallux regions in the current study was also supported by the results of the research conducted by Rao and Carter (2012), and Kim et al. (2013). These studies pointed out higher pressure-time integral values under the above regions during stair ascent with compared to a level walking task. Possibly, the explanation for this outcome is that there is a longer contact time of uphill step contact by older people associated with a slower gait speed during an uphill climbing task (Lundeen et al., 1994; Maluf et al., 2004; Rozema et al., 1996). Thus, the increase in the contact time that appeared in Table 4.2 is more likely to contribute to increasing pressure-time integral values sustained, in particular, beneath the forefoot site for this age group (Rao and Carter, 2012), as the dominant contact during the entire stance phase took place in the forefoot region, particularly with these functional activities (McFadyen et al., 1988).

In terms of the demonstration of the alteration in gait loading patterns between level and downhill walking conditions, it was suggested to discuss whether the downhill functional task would have an influence on changing the plantar pressure distribution relative to horizontal walking on a level surface being measured and compared for twenty older adult subjects. Being able to understand these differences can be useful not only for research innovations but also for supporting the clinical evaluation for specific plantar pressure parameters, which can be utilised as an efficient way to observe and monitor the maximum levels of foot stress while older adults perform downhill walking through daily activities. The results pointed out the remarkable impact of adopting downhill walking tasks on dynamic contact area parameter, revealing a number of differences between this walking task and level walking. The corresponding findings showed lower contact area values at all selected anatomical plantar regions under downhill walking conditions compared with level walking. The result was in line to some extent with the study conducted by Kim et al. (2013), who identified the plantar pressure distribution during level walking and stair descent for subjects with asymptomatic flexible flatfoot. The study revealed lower contact area under the heel, third and fourth metatarsal heads, and the hallux regions during stair descending compared to those of level walking.

Contact pressure readings, measured in the current study, have a slight reduction under most of the selected plantar regions in a downhill walking task compared to normal walking on a level surface; however, the hallux area had significantly higher plantar pressure values for downhill gait status relative to the level walking conditions. The higher contact pressure value located at the hallux region was confirmed by the study undertaken by Mattar et al. (2015), which ascertained that the pressure completely shifted towards the forefoot area while descending the stairs. The study also noticed that there was a modification in plantar pressure distribution at the forefoot site in downhill walking conditions. It might be suggested that the forefoot region would exert more pressure during downhill walking as a way to maintain balance control and posture to avoid the risk of falling because of advancing age, and that can be observed from the high amount of contact pressure distributed at the hallux region for downhill walking steps implemented in the current work.

The findings demonstrated that there were no statistically significant differences of the force values under the whole foot, heel, mid-foot, and forefoot regions between level and downhill walking conditions performed by older adults. Despite the fact that the results of the force measures revealed no significant difference between the two above walking activities beneath most of the selected foot regions in the current study, the contact area was lower for downhill walking status relative to level walking. Consequently, this means that the approximate amount of force values applied to a smaller area can have a more harmful influence under that specific plantar region, which would be the major cause of serious injuries (Ko et al., 2012). The regions with smaller area values in our study were detected in the downhill walking task. Thus, the older adults participating in the study would be more affected in a harmful way with the latter walking conditions under the whole foot, heel, mid-foot, and forefoot regions.

Additionally, the results exhibited higher force reading at the hallux region under downhill walking conditions compared to straight walking on a level surface. As has been mentioned earlier, the surface area contacting the ground during level and downhill walking activities at the hallux area had approximately the same readings. As a consequence, increasing the applied force over one of the two adopted walking conditions under a specific plantar region may result in foot plantar harassment and may lead to the development of foot deformities (Ko et al., 2012), which can increase the possibility of the risk of injuries and the occurrence of hallux valgus complaints (Putti et al., 2007) sustained by this age group, which was a main concern of the current research. People with this foot deformity have been shown to have increased mean peak pressure values under first, second, and third metatarsal head sites accompanied by increased contact time for the stance phase of the gait cycle under level walking conditions (Martínez-Nova et al., 2010; Mickle et al., 2011; Nix et al., 2013; Plank, 1995). A number of studies were conducted to investigate this specific foot condition encountered by older people (D'arcangelo et al., 2010; López et al., 2016; Mickle et al., 2009; 2011; Nguyen et al., 2010; Nix et al., 2010), which could lead to impairment of body balance, increased risk of falling, and gait instability, particularly during walking on irregular surfaces (Menz et al., 2005; Mickle et al., 2009; 2011). Therefore, higher peak plantar pressures located under the forefoot and hallux regions can possibly be utilised as a preliminary predicted sign to develop this foot condition, which can be clinically significant (Plank, 1995).

Generally, the older adults' group has a tendency to shift the plantar pressure toward the forefoot region due to the alteration in foot sensitivity accompanied with age-related changes. Consequently, the forward shift of the plantar pressure is possibly adopted by those people as a mechanism to maintain their body balance during weight bearing tasks for horizontal walking on a level surface (Franco et al., 2018; Machado et al., 2016; McKay et al., 2017). It is believed that this strategy might be more needed while more challenging functional tasks like downhill walking are encountered in daily activities by people of this age. The downhill walking task displays a substantial increase in peak pressure measures compared to walking across a level surface beneath the whole foot, forefoot, and hallux regions. It could be argued that the trend from older adult subjects to be on a longer contact time to complete the entire stance phase during downhill steps task, as appeared in Table 4.2, could diminish the peak pressure values as hypothesised by Ho et al. (2010), who emphasised that higher peak pressure readings were associated with increased walking speeds (Burnfield et al., 2004; Segal et al., 2004). However, the study results of this investigation still demonstrated an excessive increase in peak plantar pressures at the above three mentioned regions even with a decrease in walking speeds while performing downhill walking steps, reinforcing the findings from research undertaken by Urry (2002). Urry (2002) study evaluated the pressure parameters for healthy adult subjects and found that peak pressures increased under the first metatarsal, second to fourth metatarsal head, and the hallux sites during downslope walking compared to level walking conditions. This might possibly develop plantar ulcers, which have found to be associated with elevated peak pressures beneath specific plantar regions (Urry, 2002). For instance, plantar ulceration was found to be occurred for diabetic patients with approximate 10 - 20 % resulting from skin breakdown (Frykberg et al., 1998; Stess et al., 1997; Veves et al., 1992) under the first and fifth metatarsal head sites as these two regions demonstrated higher pressure values (Urry, 2002; Veves et al., 1992).

The high amount of peak pressure distributed at the hallux region of our own study was supported by a previous study conducted by Grampp et al. (2000) for a 15% downhill gradient. It might be considered that higher peak pressure values measured for a group of older adults performing in this study under the hallux region were attributed to increasing the foot inversion for providing a stable level of balance to terminate the stance phase accompanying the downhill walking condition (Ho et al., 2010), and this has been demonstrated from the high amount of force beneath the hallux region for downhill walking tests relative to level walking condition trials.

The current work evaluated the influence of both level and downhill walking conditions on the redistribution of temporal characteristics of foot loading data beneath the specified plantar regions for a group of older adults. There were significant variations between the two walking tasks, pointing out a higher force-time integral for downhill walking steps registered under the whole foot, forefoot and hallux regions in relation to those measured under normal walking conditions. Furthermore, the results revealed that pressure-time integral values were statistically higher at the whole foot, heel, forefoot, and hallux regions for downhill gait steps compared to normal walking. This finding was in close agreement with results reported in studies undertaken by Rao and Carter (2012), and Kim et al. (2013), who emphasised higher pressure-time integral readings detected under forefoot and hallux areas while descending stairs in relation to normal level walking. However, these studies have been performed for young adult subjects. The higher pressure-time integral measures located under all specified plantar regions in the current work could relate the fact that older adults attempt to reduce walking speeds in order to avoid or prevent falls accompanied by downhill activities (Mattar et al., 2015). Furthermore, it is important to mentioned that the redistribution of peak pressure magnitudes for downhill gait steps is noticeable with an increase in these measures, particularly beneath the forefoot and hallux regions compared to level walking, owing to the need to exert more peak pressure under these areas for the purpose of maintaining body balance along the push-down and toe-off phases of the stance phase of the gait cycle (Mattar et al., 2015). To sum up, higher peak pressure values with longer contact time are required to terminate the stance phase of the gait cycle during downhill walking steps undertaken by older adult individuals participated in the current study. The higher peak pressure values accompanied by a longer contact time could result in foot complaints and possibly foot deformities, leading to an increase in the risk of foot injuries, in particular beneath the forefoot and hallux regions.

In conclusion, the alteration in plantar loading patterns during uphill and downhill walking steps performed in the current work by a group of older adults can provide an indication that the plantar pressure redistribution might prohibit providing the sufficient stabilisation to safely accomplish these two activities for people from this age stage. Therefore, a number of clinical interventions, or even the provision of optimal insoles designed based on the research outcomes might be beneficial for older people.

4.7 Case studies for a number of selected older adult subjects

4.7.1 A case study for the Centre of Pressure (COP) trajectory for older adult individual 1

From the study conducted, the video captured plantar patterns during walking in various activities for an older male subject aged 68 years in the uphill walking steps condition; the COP trace started from the centre of the mid-foot area as the subject commenced the gait cycle with initial contact by both heel and forefoot regions. The COP trace then rapidly moved toward the forefoot as this area had more peak pressure values compared to other foot regions during the initial contact of uphill gait activity. After which, during foot-flat and mid-stance phases, the COP trace slightly stepped back again to the mid-foot region, followed by moving again toward the forefoot region for observational preparation for the push-down phase. The COP trace then had an obvious deviation toward the hallux area and back again at the medial part of the forefoot region to terminate the stance phase at toe-off. In this phase, the subject was weight bearing on the forefoot region, particularly at the medial part, continuing until the last frame of the stance phase of the gait cycle. Thus, an attempt from this older subject was made to apparently keep and maintain the body balance during uphill walking steps task, which was achieved with abnormal COP trajectory relative to normal walking on a level surface. The COP trajectories for level and uphill gait conditions for this older adult subject appear in Figures 4.18, and 4.19.

The COP for this older subject was located centrally as usual in the middle of the heel area at heel-strike phase, persisting at this area with the task of downhill walking steps for a longer period of time compared with walking on level surfaces as an attempt to maintain the body balance required for proper initiation of the downhill walking condition. This was evident from the higher amounts of force-time integral and pressure-time integral under the heel area during the downhill walking condition in relation to that for horizontal walking activity, as presented in Figures 4.16, and 4.17. The COP trace then moved in a straight line, overriding the mid-foot area within a small number of frames, toward the forefoot area. The COP trace then had some hesitation at the forefoot area, particularly under the medial forefoot part. This can be demonstrated from the higher values of peak pressure, force-time integral, and pressure-time integral under the forefoot region accompanied by downhill walking steps compared to the level gait condition, as has been shown in the results section of this chapter. The COP trajectory at this stage can be explained as an endeavour from the subject to create the body balance necessary to overcome the slips that might occur while performing downhill gait activities by people from this age stage. The COP trace eventually had a deviation toward the hallux area, having an excessive increase in contact pressure, force, peak pressure, force-time integral, and pressure-time integral for downhill gait with relative to level gait conditions, as mentioned in the results section of the current chapter. The higher measures for all above mentioned plantar parameters with longer time taken by the older subject under the hallux area during downhill walking could be due to an adapted mechanism for safely terminating the stance phase of the gait cycle, particularly during push-down and toe-off phases. The longer contact time during these two phases was a trend from the older subject because of weight bearing under this area thereby attaining the body balance required to prevent slip away expected with downhill gait tasks for people with advancing age. The COP trajectory for this older subject during downhill walking condition is displayed in Figure 4.20.

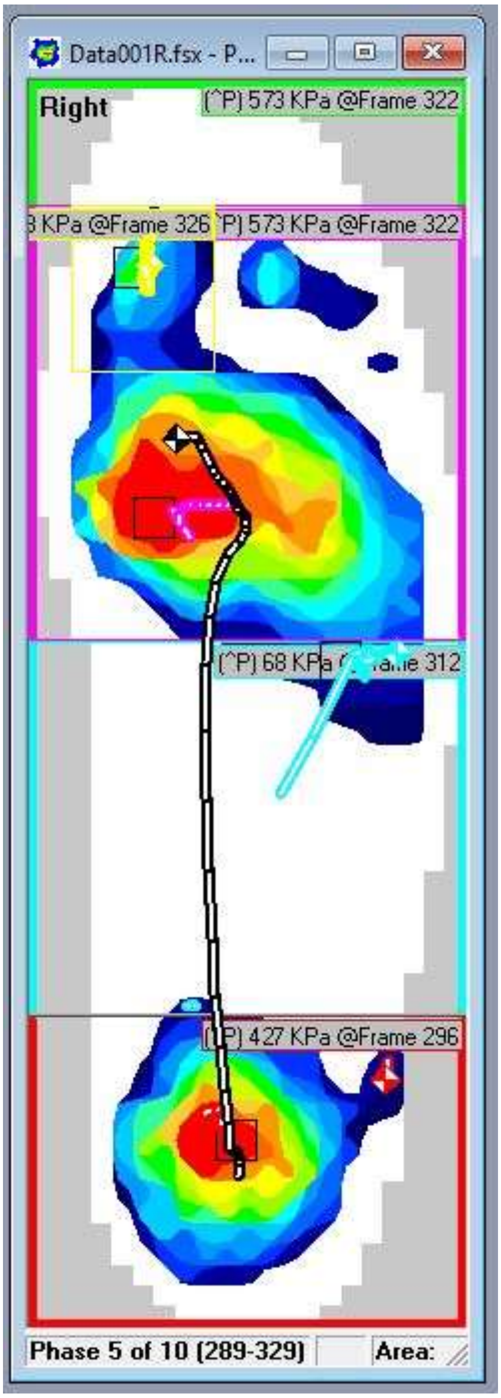

Figure 4.18: Plantar pedobarographic image for older adult subject showing COP trajectory for level walking condition.

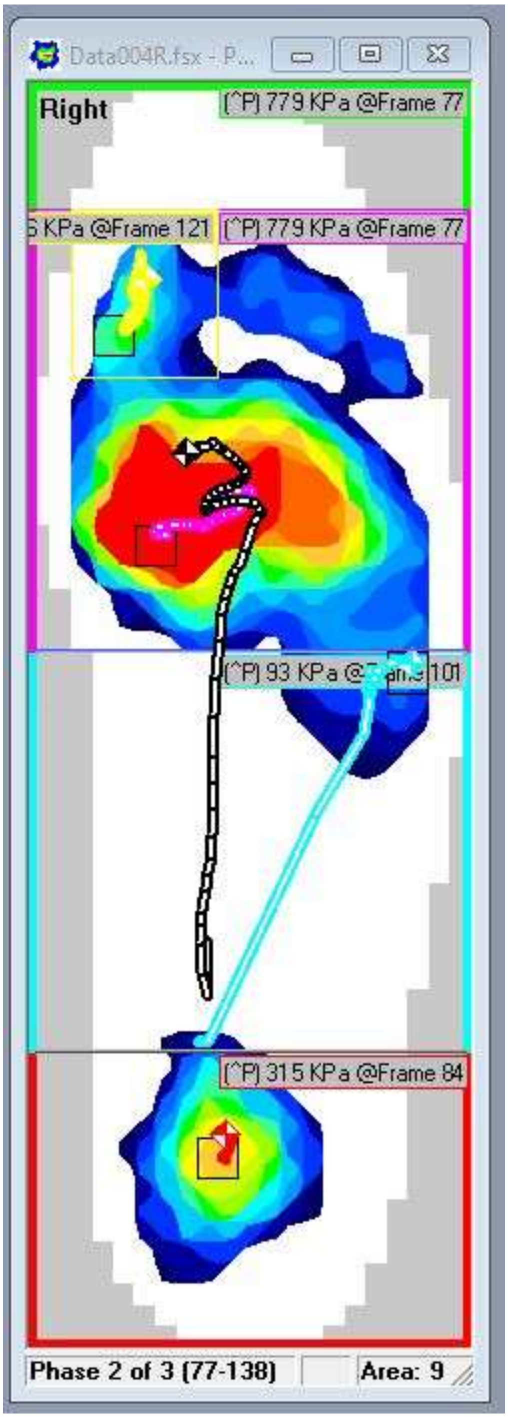

Figure 4.19: Plantar pedobarographic image for older adult subject showing COP trajectory for uphill walking steps task.

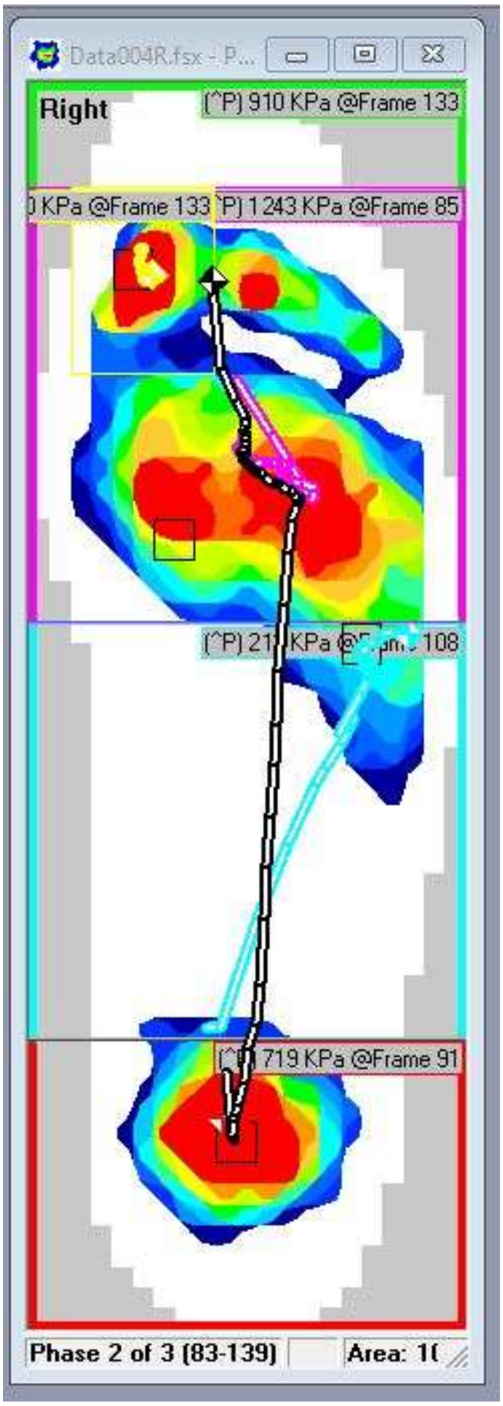

Figure 4.20: Plantar pedobarographic image for older adult subject showing COP trajectory for downhill walking steps task.

4.7.2 A case study for the Centre of Pressure (COP) trajectory with relevant plantar pressure parameters for older adult individual 2

The older male subject aged 72 years with a weight of 93 kg has started by contacting the ground at the heel-strike phase with normal walking conditions on a level surface at self-selected speeds with a force value of 35 kg, reaching 118 kg as a force value at the end of this phase with whole contact by heel area with the ground. After a few frames, in the foot-flat phase at the loading response, the subject had a weight acceptance with force value recorded at 93 kg, reaching the subject's weight. At mid-stance phase, the value of force was 58 kg, which was more than half the subject's weight. The value of the force at push-down phase with terminal stance reached about twice the subject's weight. This could be due to the mechanism of forward shift of the plantar pressure toward the forefoot area as a result of the alteration in foot sensitivity occurred due to age-related changes, as considered in the discussion provided in section 4.6. The force value at toe-off phase for this older subject was 23 kg during normal walking.

However, for the same older subject with the uphill walking condition, the force value was 17 kg with the commencement of the stance phase of the gait cycle at heel-strike phase, in which the COP was centrally located at the middle of the heel area, proceeding toward the mid-foot region. At the loading response phase, the force value was 60 kg. The COP trace stepped back towards the heel area as this area for the tested older subject had higher force value compared to the forefoot area during the foot-flat phase.

At the beginning of the mid-stance phase, the COP was turned around to proceed forward to the mid-foot and forefoot regions. The force value at this stage was 93 kg, maintaining the weight acceptance case with force values between 90 – 95 kg for a certain number of frames. The subject was weight bearing on the tested foot while performing an uphill gait task as an attempt to maintain the balance necessary to overcome obstacles and prevent slips accompanied with walking on inclined surfaces. In particular, this refers to older people during the mid-stance phase, when one limb has to be responsible for carrying the body weight. During the terminal stance at the push-down phase, the force value gradually decreased to eventually reach out to 12 kg at toe-off phase, which ends the stance phase of the gait cycle. The force graphs for both walking on a level surface and uphill walking condition are shown in Figure 4.21.

The older subject aged 72 years, with downhill walking conditions, started the initial contact with peak pressure value of 265 kpa at the heel region, which was lower than that for the subject walking normally on a level surface. The subject's peak pressure value of 757 kpa was recorded at the heel region in one of the test gait trials under a level walking condition. After a few frames from the initial contact phase, the subject had touched the ground, as noticed from the captured video, reaching peak pressure of 459 kpa at this early stage during the foot-flat phase of the stance phase of the gait cycle under the forefoot area. It seems that the subject had started to shift the body weight earlier toward the forefoot area for downhill gait as a way to maintain the body balance required for this gait task as has been discussed in section 4.6 provided in the current chapter. Then, the COP trace has rapidly moved in a straight line toward the forefoot, particularly in its medial part with an excessive increase in the peak pressure value 533 kpa at the forefoot area during the mid-stance phase.

From monitoring the video captured for the subject plantar surface during downhill gait task, it seems that the older participant spent more time in both push-down and toe-off phases compared to other phases. The COP trace had some hesitation in the forefoot area, particularly under the first and second metatarsal heads, having the highest peak pressure value at push-down phase 1096 kpa, specifically under the hallux area, which has been earlier presented in the results section of this chapter. The COP then had a sharp deviation toward the hallux area to complete the stance phase of the gait cycle in particular at toe-off phase with peak pressure measure of 395 kpa beneath this area. The peak plantar pressure graphs for both walking on a level surface and downhill walking condition are shown in Figure 4.22. The plantar pedobarographic images for the tested older adult subject, showing COP trajectory for level, uphill and downhill gait tasks measured in F-Scan Research software appear in Figure 4.23.

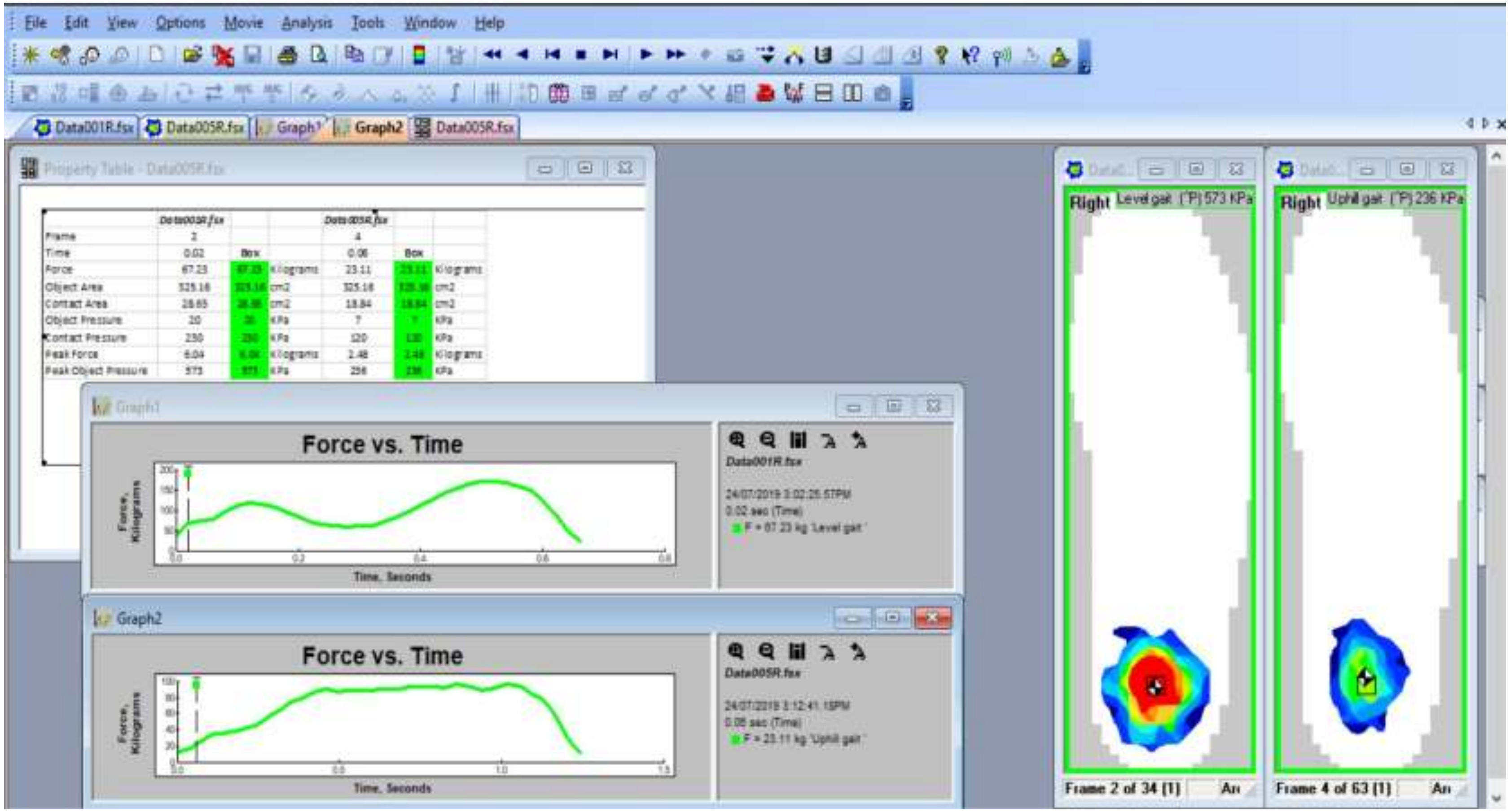

Figure 4.21: The force graphs for level and uphill walking conditions showing the force values for the entire stance phase of the gait cycle for the older adult subject whole foot in each gait task.

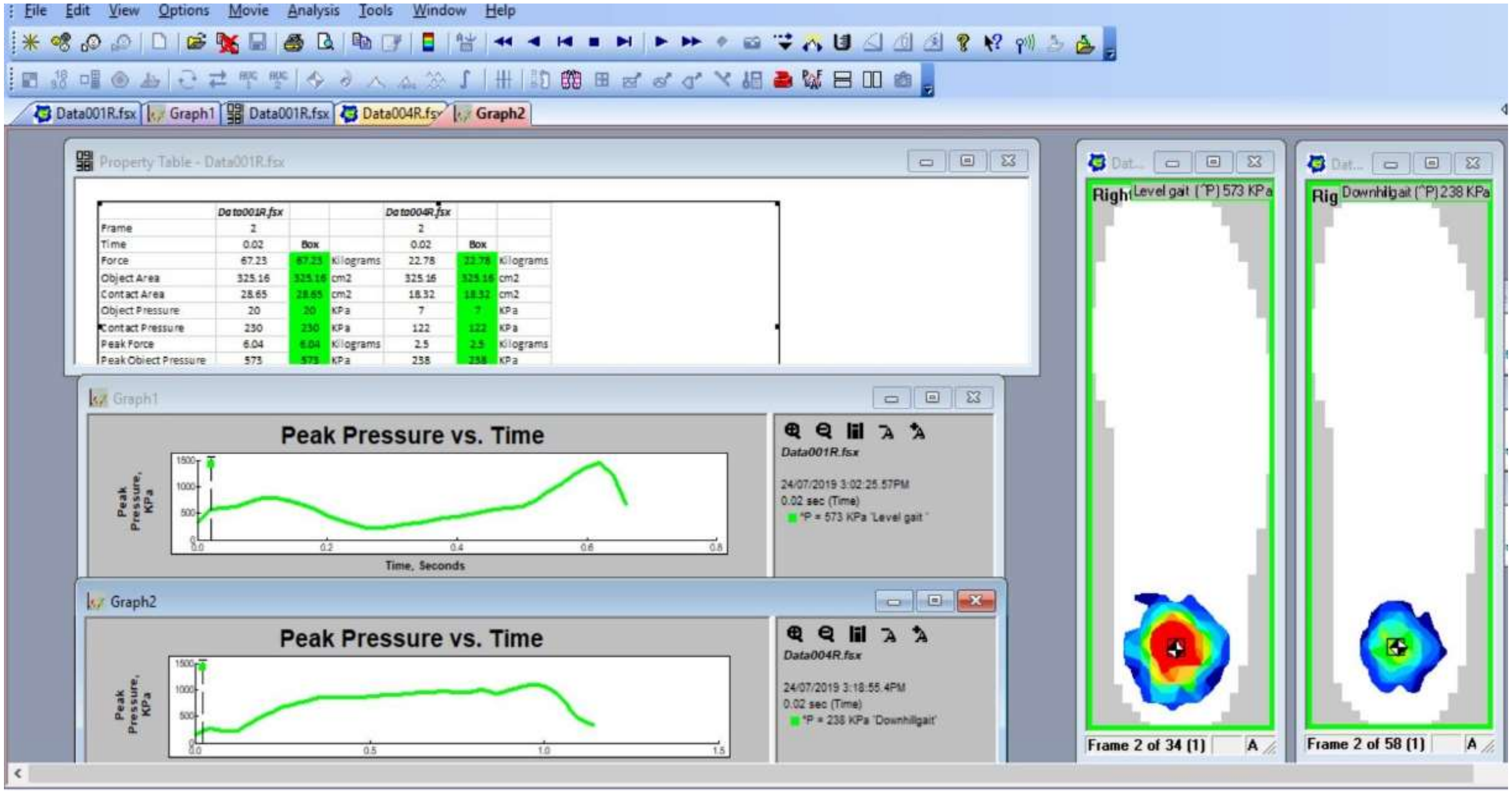

Figure 4.22: The peak plantar pressure graphs for level and downhill walking conditions showing the peak pressure values for the entire stance phase of the gait cycle for the older adult subject whole foot in each gait task.

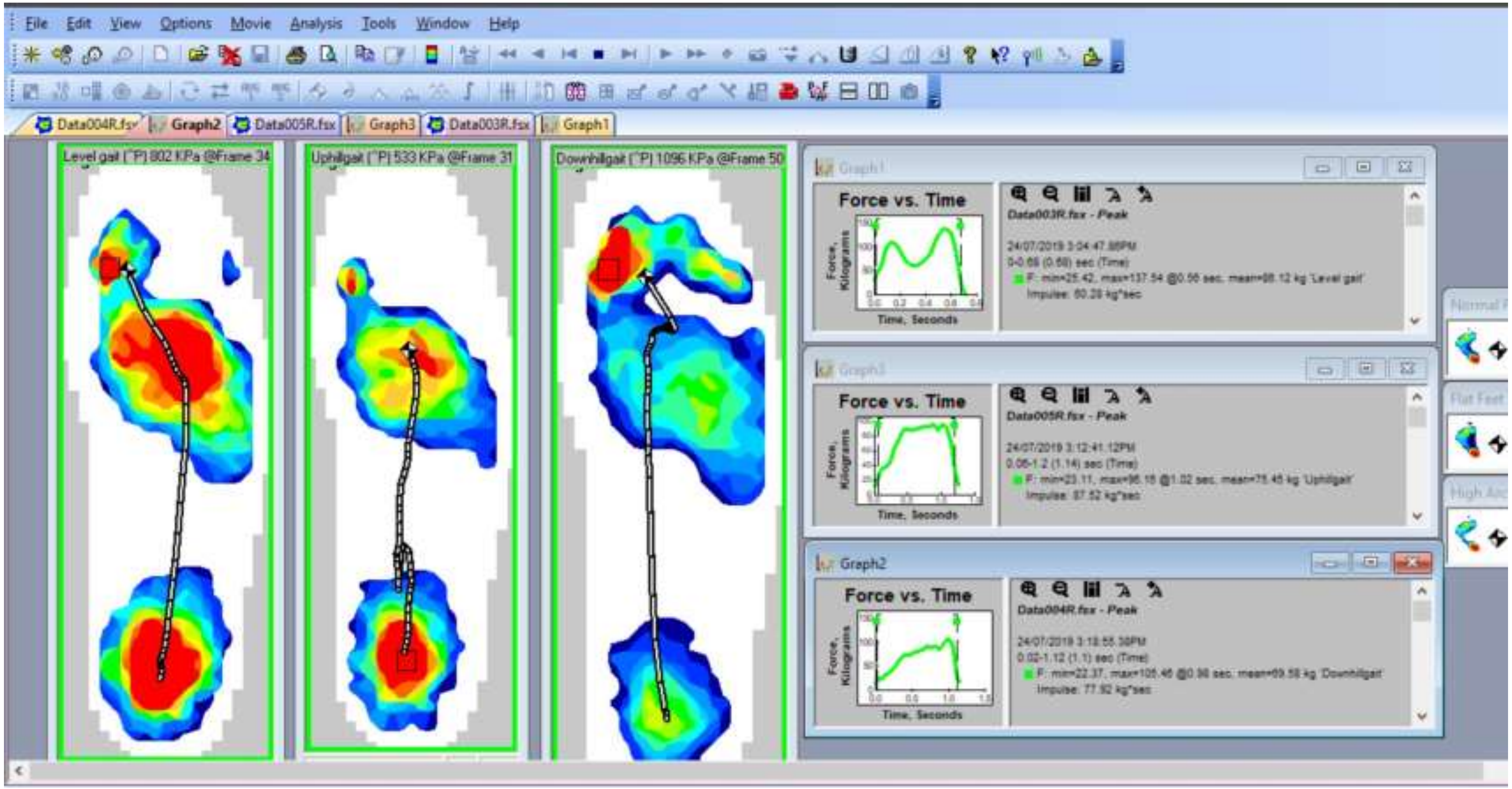

Figure 4.23: Plantar pedobarographic images for older adult subject showing COP trajectory for level, uphill and downhill gait tasks measured in F-Scan Research software.

4.7.3 A case study for the Centre of Pressure (COP) trajectory with relevant plantar pressure parameters for older adult individual 3

The COP for this older woman subject aged 73 years started from a point before the heel down, and continued centrally along the entire length of the foot with a slight deviation toward the lateral side of the plantar, as noticed from the video captured on the plantar surface via F-Scan Research software system while performing level walking conditions at self-selected speeds. The COP had reached to the point at the middle of the forefoot area under the second metatarsal head and did not go further toward the hallux area. Observationally, the older subject had terminated the stance phase of the gait cycle without the need to depend on the hallux and lesser toes at toe-off phase. This could be noticed from the small amount of contact area at the hallux region, which was 6.5 cm^2. This was also evident from the small value of peak pressure recorded at this area, which was 98 kpa during level walking conditions. The highest peak pressure was 1109 kpa in the last frame of the stance phase and that was under the metatarsal heads.

For this older subject, the mean contact time for the whole stance phase of the gait cycle for level and uphill walking conditions was (0.6, 0.825 sec), respectively. Regardless of the fact that the difference between these two figures is not high, the subject had taken twice the time in push-down and toe-off phases during the uphill gait task than that taken for level walking conditions. The subject had twenty five frames during these two phases while performing uphill gait steps task with only twelve frames for normal walking on level surfaces.

From monitoring the videos captured for the plantar surface, the subject started earlier to contact the ground with the forefoot area, proceeding until the end of the entire stance phase for uphill gait task. This means that the length of contact for uphill walking at the forefoot area, particularly under the metatarsal heads was higher than that for the subject level walking. The length of contact for the forefoot region reached 92% of the whole stance phase during the uphill gait task, while it was 75% for the level walking condition, as appeared in Table 4.17, adopted from the reports which analysed plantar pressure patterns for each subject. Beyond that, the subject started making contact with the ground with the forefoot area within 8% of the stance phase commencement and that was specific under the second and third metatarsal heads for the uphill gait task, whilst the subject initiated contact with the ground with the second, third, and fourth metatarsal heads starting from about 25% from the beginning of the stance phase for the subject level gait. It seems that this subject had a tendency to spend more time in push-down phase as a way to maintain the necessary body balance while performing a walk on the ascent planes.

Additionally, it is worth noting that while performing the uphill gait task, the subject had to bear the body weight on the forefoot area, recording the highest peak pressure values for approximately seventeen frames, as noticed form screening the video captured for the subject’s uphill gait activity. This could cause tissue injuries under the forefoot area if the subject had to perform the uphill walking steps multiple times during daily activities, as mentioned earlier in the discussion provided in section 4.6. However, the subject had high peak pressure measures for about seven frames in level walking conditions. The COP trace started at the heel region, proceeding forward rapidly in a straight line toward the forefoot area, having a hesitation under the forefoot area as described earlier, which could develop tissue injuries beneath that area if the older subject had to perform uphill gait steps for such a long period of time during the day.

Table 4.17: Length of time taken by the older subject in a number of plantar regions under three conditions: level walking, uphill walking steps, and downhill walking steps task, adopted from the reports provided by the plantar pressure measurements system, FSCAN Research, version 6.7 software.

		TF	MH	LH	MF	M1	M2	M3	M4	M5	T1	T2	T3	T45
Level	**Length (ms)**	580	336	336	476	336	418	435	435	394	139	215	215	133
	Length (%)	100	58	58	82	58	72	75	75	68	24	37	37	23
	Begin (%)	0	0	0	4	42	28	25	25	32	76	63	63	76
	End (%)	100	58	58	86	100	100	100	100	100	100	100	100	99
Uphill	**Length (ms)**	780	296	296	671	655	718	718	694	640	273	257	257	351
	Length (%)	100	38	38	86	84	92	92	89	82	35	33	33	45
	Begin (%)	0	0	0	11	16	8	8	11	18	65	67	67	54
	End (%)	100	38	38	97	100	100	100	100	100	100	100	100	99
Downhill	**Length (ms)**	660	416	416	330	337	535	535	515	370	396	337	297	218
	Length (%)	100	63	63	50	51	81	81	78	56	60	51	45	33
	Begin (%)	0	0	0	10	49	19	19	22	43	40	49	55	67
	End (%)	100	63	63	60	100	100	100	100	99	100	100	100	100

For which:

TF- Total foot, MH- Medial heel, LH- Lateral heel, MF- Mid-foot, M1- First metatarsal head, M2- Second metatarsal head, M3- Third metatarsal head, M4- Fourth metatarsal head, M5- Fifth metatarsal head, T1- Toe 1, T2- Toe 2, T3- Toe 3, T45- Toe 4, and 5.

The COP trajectory for this older subject and during the downhill walking steps task started from the middle of heel region, moving in a line forward to the forefoot area with some hesitation at this area to eventually move toward the hallux region with higher values of contact pressure and peak contact pressure when compared to the level walking condition. The mean contact pressure and peak pressure for normal walking and downhill gait steps at the hallux region were (contact pressure: 104, 428.33 kpa) and (peak contact pressure: 193, 1164.67 kpa), respectively. From monitoring videos capturing the subject while undertaking downhill walking steps, the subject contacted the ground with the forefoot area after ten frames from the stance phase commencement for the downhill walking task, being in contact with the ground at this area until the last frame of the stance phase of the gait cycle at toe-off phase. This might cause tissue injuries under the metatarsal heads and the hallux area, which has been demonstrated in the discussion provided in section 4.6. This was evident from higher peak pressure values recorded in these regions under downhill walking conditions compared with level walking, as presented in the results provided in section 4.5.

Furthermore, for this older subject, having higher peak pressure values during the push-down phase for a longer time of about ten frames more when compared with the subject's normal walking on a level surface could develop foot complaints beneath the forefoot area. The risk of the development of foot complaints would be greater if the subject had to walk on descending surfaces more than is usual for older people. In addition, the subject had a small pressure amount in the mid-foot area recorded for the downhill walking tasks. This area contacted the ground at late stage of the stance phase, which was during the push-down phase. It is worth noting that the subject had normal common contact with the mid-foot area within the foot-flat phase during level walking conditions.

Because the subject spent longer time when performing the downhill gait task, the force-time integral and pressure-time integral values were higher than that measured for level walking, particularly in forefoot and hallux regions. This means that performing downhill walking steps by this older subject might lead to foot injuries, especially under the above mentioned regions. The plantar pedobarographic images for the tested older adult subject, showing the COP trajectory for level, uphill and downhill gait tasks measured in F-Scan Research software along with graphs, displaying the peak pressure measures under the main foot regions specified in the current work in relation to the number of frames taken in each gait task, appear in Figures 4.24, 4.25, and 4.26.

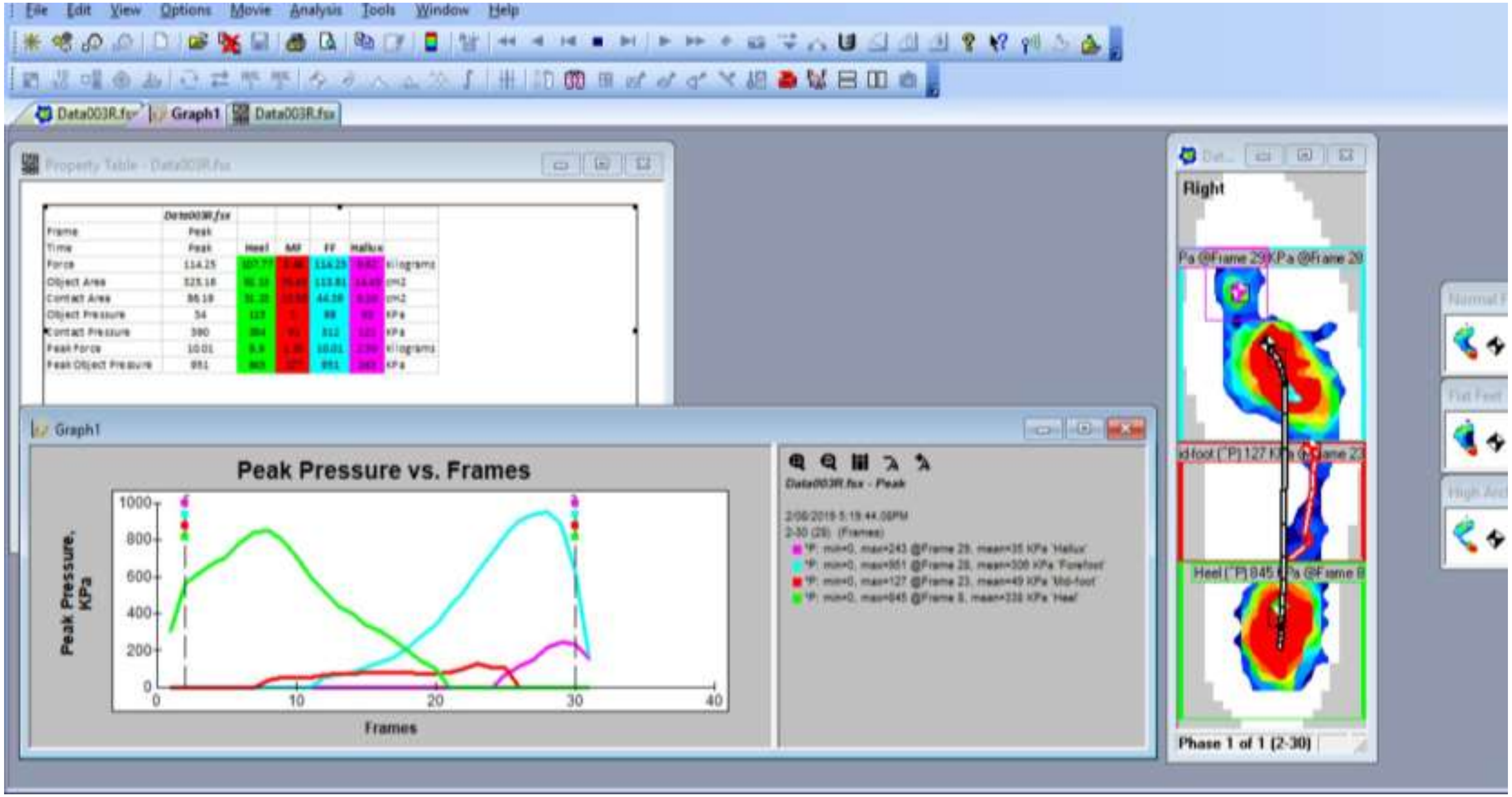

Figure 4.24: Plantar pedobarographic image for older adult subject showing COP trajectory with peak pressure values graph measured in F-Scan Research software under main plantar regions for level walking condition.

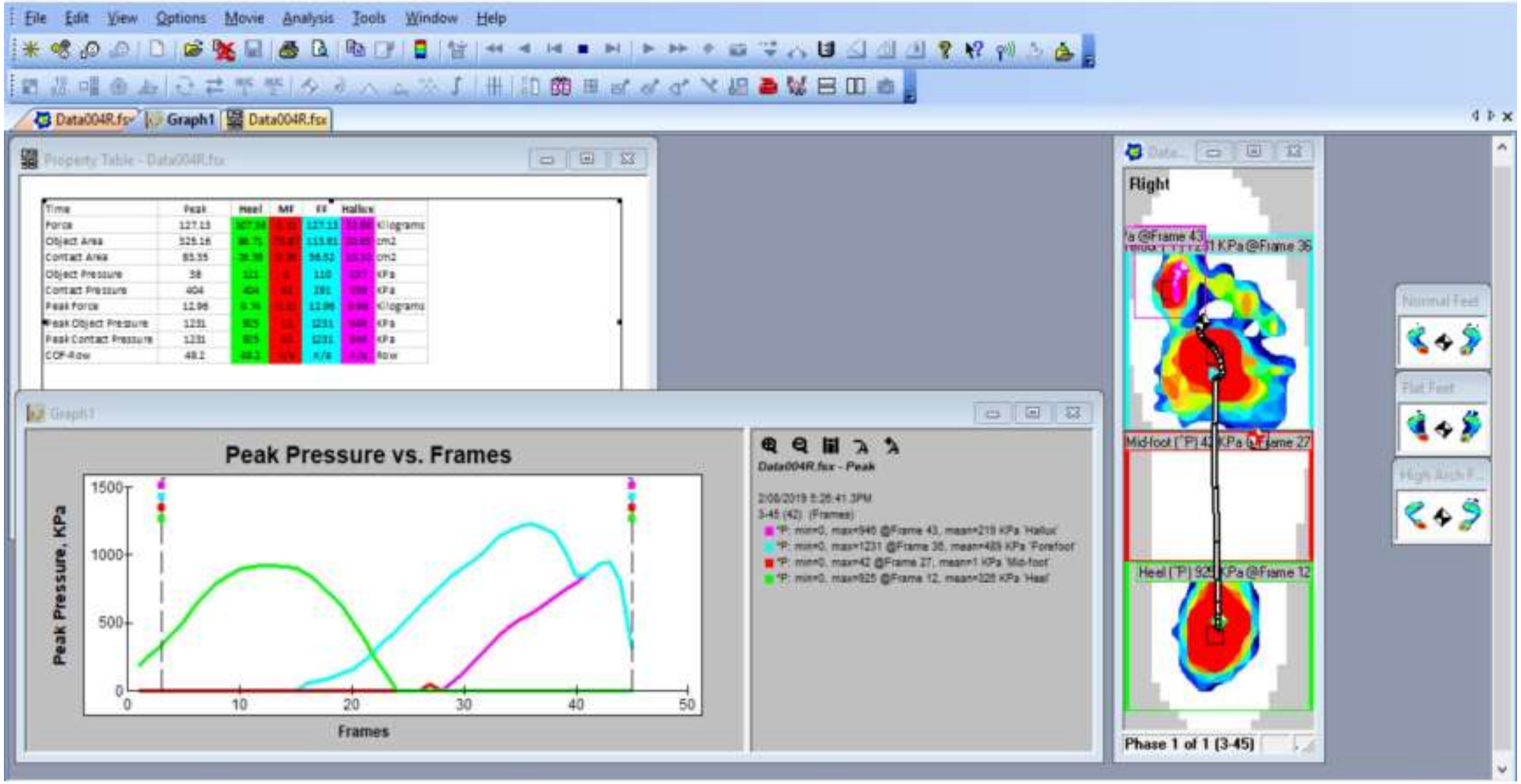

Figure 4.25: Plantar pedobarographic image for older adult subject showing COP trajectory with peak pressure values graph measured in F-Scan Research software under main plantar regions for uphill walking steps task.

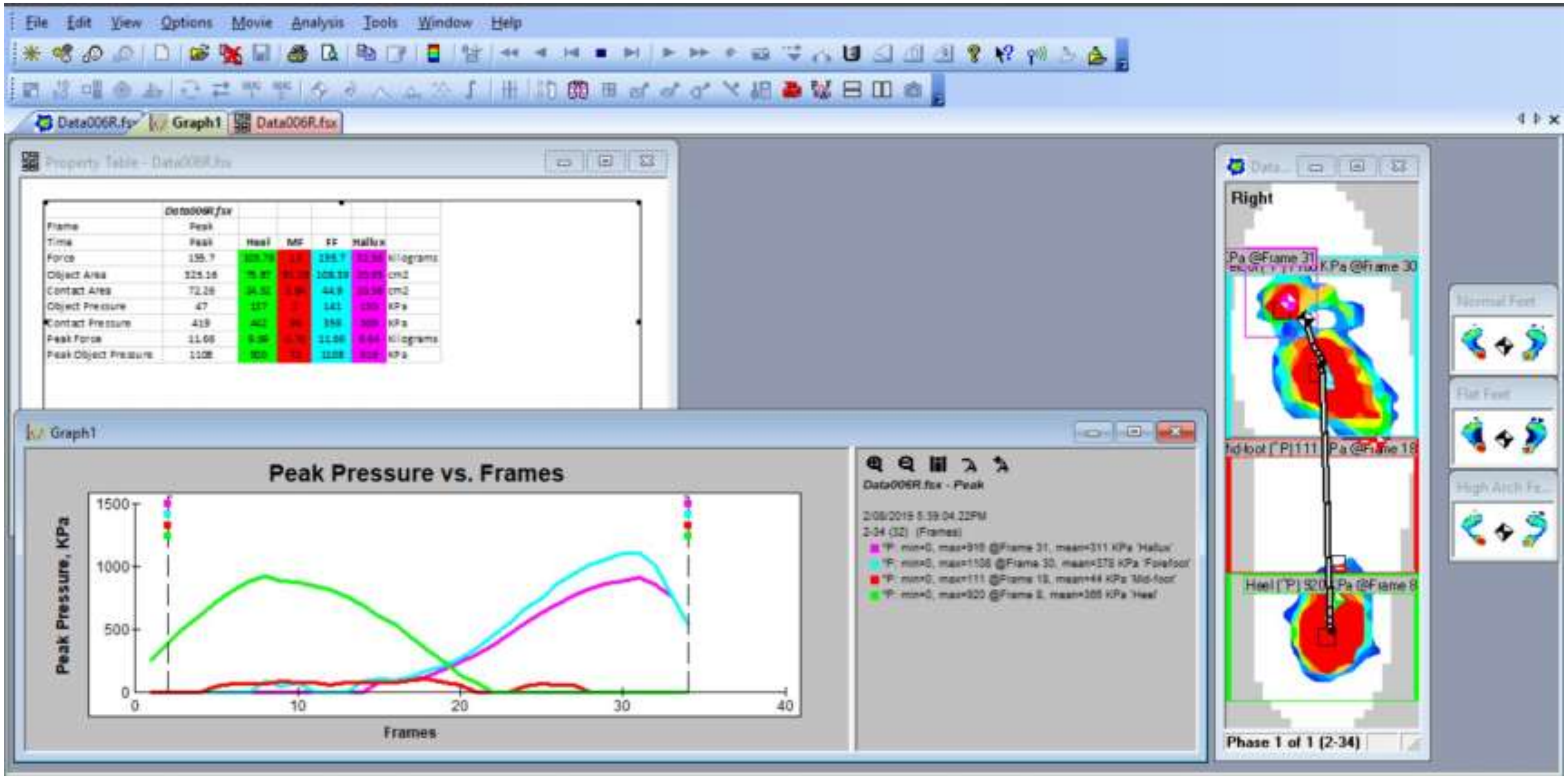

Figure 4.26: Plantar pedobarographic image for older adult subject showing COP trajectory with peak pressure values graph measured in F-Scan Research software under main plantar regions for downhill walking steps task.

4.8 Conclusion

As the surfaces of outdoor walking are not flat in general, the demands required to maintain balance during walking can vary depending on whether they are level or sloping surfaces. From the previous studies relevant to older people's gait, little is yet known about its plantar pressure pattern variations between level and inclined surfaces. The aim of the study was to investigate plantar pressure distribution differences between level and uphill and downhill walking steps for a group of people from this age beneath five anatomical foot regions during the entire stance phase of the gait cycle, wearing pressure sensor insoles.

The results showed higher plantar pressure measurements, including contact pressure, peak pressure, force-time integral, and pressure-time integral values, particularly under the whole foot, forefoot, and hallux regions accompanied by lower contact area measures beneath these areas for uphill walking condition compared to level walking. For downhill walking tasks, the results revealed an excessive increase in peak pressure, force-time integral, and pressure time integral values underneath the whole foot, forefoot, and hallux regions in relation to that of level walking condition.

The research provided an evaluation of plantar pressure measurements for older people during different walking tasks. This could enhance the visualisation of the pressure measures distributed under the whole foot plantar related to each specific walking condition, which can contribute to comprehensively understanding the balance problems associated with each of these gait tasks. Being able to understand the discrepancies in plantar pressure patterns for walking on inclined surfaces in relation to normal gait on level surfaces, that can be the reasons for deterioration of the balance ability, can assist to provide optimised customised foot wear design to suit older people's needs, which may minimise the risk of falling with advancing age during walking on inclined surfaces. Additionally, the obtained peak pressure findings while walking on level surfaces may assist in efficiently detecting the stress levels during the gait on inclined surfaces underneath various main foot regions for older adults through comparing the outcomes with uphill and downhill walking conditions. Furthermore, the outcomes of the plantar pressure parameters for the three walking conditions adopted in the present study for a number of older adults can provide an assessment, which could be referred to as a reference value by clinicians for the pathological diagnosis and injuries treatment for older people from the same age in relation to these walking tasks; hence, the study could be clinically significant. The next chapter addresses the plantar pressure measurements captured for five phases included in the stance phase of the gait cycle for the comparison between older adults and adults.

CHAPTER FIVE

PLANTAR PRESSURE CHARACTERISTICS COMPARISON DURING HEEL-STRIKE, FOOT-FLAT, MID-STANCE, PUSH-DOWN AND TOE-OFF PHASES OF GAIT BETWEEN OLDER ADULTS AND ADULTS

5.1 Introduction

Due to age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during gait, could result in serious injuries. The risk of falls sustained by older people can increase because of stability and balance impairment, which in turn may impair the foot function during normal gait. It is well known in previous studies that most foot problems, including falls encountered by older adults, occur during gait. Furthermore, the scientific and clinical evaluation of foot and gait pathologies can be obtained by performing plantar pressure distribution measurements. Therefore, the first purpose of this doctoral research was to evaluate the plantar pressure patterns for older adults and adults during five gait phases included in the stance phase of the gait cycle, whereby the foot is in contact with the ground under fifteen anatomically defined foot regions, covering the whole plantar surface to thoroughly study and understand the underlying causes of a lack in maintaining the human body balance during gait with advancing age. This purpose includes finding out whether the foot complaints and balance impairments encountered by those people have been associated with specific phases of the gait cycle. Moreover, the second purpose of the research was to study whether taking into account the data normalised to subjects' body weight, and to the time required to finish the stance phase had implications on pressure and peak pressure comparisons for the two cohorts. Fourteen participants, eight older adults and six adults, were recruited in the study to perform typical barefoot walking. The study revealed higher values of contact pressure and peak plantar pressure for the older adults' group in a number of plantar regions, particularly during the mid-stance, push-down, and toe-off phases. These higher values were located under the forefoot area, in particular at the metatarsal heads and the hallux regions, showing that, for people of this age, these regions could be considered vulnerable among the whole plantar surface. Furthermore, weight and time normalised data revealed higher values under the selected plantar regions, except the regions of heel and second toe for the older adults' group, which had lower values of pressure and peak pressure when compared to the adults' group during the mid-stance phase. Therefore, the weight and time normalised values analysed during the mid-stance phase showed similar comparisons with respect to the un-normalised data in terms of higher contact pressures and peak pressures in most of selected plantar regions for older adults compared to those obtained for adults.

5.2 Background

The human body part that connects the human body with the ground is the foot, which is integral to human gait (Rodgers, 1995). Human gait can be utilised for assessing the quality of life, the health condition, and the physical functioning of older people (Cesari et al., 2005; Hollman et al., 2011). Due to age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during ambulation often result in injuries (Day, 2003; Lord et al., 2007; Menant et al., 2008; Mickle et al., 2010; 2011; Rubenstein, 2006). The risk of falls of older people can increase as a consequence of stability and balance impairment caused by factors, which may impair foot function during normal gait (Mickle et al., 2010). Foot pain is recognised as one foot-related factor that affects older adults in terms of gait, balance, and normal foot function (Menz et al., 2001). A number of recent studies established that there is a clear association between foot pain and elevated plantar pressures for older people during gait.

Much research has focused on and documented plantar pressure measurements considering data from the plantar phase image only. However, relatively few studies have investigated plantar pressure measurements in each specific gait phase separately. Therefore, the main aim of this study was to measure plantar pressure parameters during five phases of the gait due to the need to have a clear understanding of changes in loading patterns in these phases, representing the stance phase of the gait cycle in which the foot is in contact with the ground, via employing a comparison between older adults and adults. In doing so, the first goal of this study was to provide insights into understanding the changes occurring in plantar pressure measurements distributed in fifteen plantar regions during the main phases. At the same time it aimed to assess whether there was chance of gait impairment related to each specific phase with advancing age. Furthermore, the research aimed to study plantar pressure parameters during the first half of the single limb support interval represented as the mid-stance phase, whereby one lower limb and foot are required to support the body weight as the other limb would be in swing phase. One issue to consider was normalising the data based on subjects' weight and the total time taken to finish the gait cycle to demonstrate the influence on gait difference between the two groups participating in this study: older adult and adult.

5.3 Research methodology

5.3.1 Participants

The results of 42 trials were collected from fourteen participants who were recruited in this study: eight older adults aged 65-80 years (mean age 72.8 ± 4.9 years, weight 85.3 ± 11.4 kg, height 176.4 ± 7.6 cm, and BMI 27.7 ± 5.3 kg/m^2), and six adults aged 32-39 years (mean age 36.2 ± 2.9 years, weight 78.2 ± 4.2 kg, height 173 ± 4.4 cm, and BMI 26.2 ± 2.4 kg/m^2). The mean contact time required for accomplishing the whole stance phase for both older adults and adults was (1.07 ± 0.23, 0.72 ± 0.04 sec), respectively. Human subjects participated in this research under an approved ethical application (H18REA160) obtained from the University Ethics Committee.

5.3.2 Research equipment and theoretical tools

A number of studies have employed the Tekscan pressure systems for the measurements of plantar pressure patterns for subjects, whether healthy or with different pathologies during walking (Chevalier et al., 2010; Chong et al., 2014; Menz et al., 2006). Research showed that these systems are reliable and accurate for plantar forces and pressures for barefoot level conditions (Brenton-Rule et al., 2012; Giacomozzi, 2010; Hafer et al., 2013; Zammit et al., 2010), making these systems appropriate for both research and clinical settings (Brenton-Rule et al., 2012; Hafer et al., 2013).

The research adopted a MatScan® (Tekscan, Boston, MA) for platform based plantar pressure measurement sampling at 100 Hz to capture plantar parameters, such as contact area, contact pressure, and peak plantar pressure. Basically, the systems include a floor sensor mat (432 * 368 mm) of 5 mm thick, which consists of 2288 individual locations of pressure sensing call sensing elements with 1.4 sensors/ cm^2 as their spatial resolution. The system was calibrated prior to the gait tests session conducted for each subject. The calibration process was implemented using the body weight for each tested subject according to manufacturer's guidelines.

The subjects were asked to perform a two-step gait protocol, in which plantar parameters were recorded when second step contact was made with a Tekscan floor pressure mat (Bus et al., 2005; Chevalier et al., 2010; Meyers-Rice et al., 1994). A standard gait procedure was carried out by participants represented by the position of standing at the commencement, followed by proceeding forward to step on a pressure mat, and repeating the test three times for measurement purposes. Few minutes were given to each participant before the commencement of the gait trials to practise the test, thereby positioning the subject's foot on the floor-mat and avoiding alteration to the required step characteristics of the research.

It was necessary to ensure that the specific images, which represented the five loading phases of gait in the F-scan system were selected according to the standard level of accuracy. Therefore, the video recordings captured of participants during walking detected the gait for each subject using five video cameras prepared beforehand. The stance phase (from heel-strike until toe-off phases) for each participant was monitored to ascertain the images associated with the phases to be investigated. For instance, the mid-stance phase predominantly occurred from about 12% and continued until 31% of the gait cycle, which was in line with the studies conducted by Burnfield (2010). The time was counted from the starting point at heel-down until the required moment relevant to each phase. Doing a matching calculation to compare this time with the corresponding time in the Tekscan system, the images that represented the five phases of the stance phase had been precisely achieved.

For regional plantar pressure measurement analysis, the study used the FSCAN Research, version 6.7 software to construct individual masks under fifteen plantar regions, namely the medial heel, lateral heel, medial mid-foot, lateral mid-foot, medial forefoot, lateral forefoot, metatarsal (1, 2, 3, 4, and 5), and toe (1, 2, 3, 4, and 5). The masks were analysed to determine and study the foot loading pattern variations for the entire stance phase of the gait cycle, in particular during five loading phases of gait for older adults and adults under barefoot walking conditions via floor-based pressure mat systems shown in Figure 5.1. Figure 5.2 shows: plantar pedobarographic images for an older adult subject, displaying the fifteen plantar regions selected in the present work.

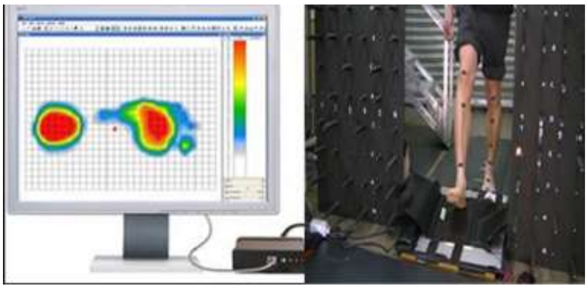

Figure 5.1: Plantar pressure measurement systems.

In the study, a number of plantar pressure parameters, namely the contact area, contact pressure, and peak pressure have been extracted for the two groups participating: older adults and adults during five gait phases within the stance phase of the gait cycle, obtained by analysing their associated plantar pressure images. These videos were captured while the subjects were walking barefoot on the pressure mat using Tekscan measurement systems in order to distinguish the discrepancies of the gait characteristics between older adults and adults during loading phase of gait. Figures 5.3, 5.4, 5.5, 5.6, and 5.7 show the images, displaying the human foot movements while the older adult was performing normal walking on the pressure mat. Simultaneously, images are shown of the plantar pressure measurement systems during the five loading phases of gait, heel-strike, foot-flat, mid-stance, push-down, and the toe-off, respectively.

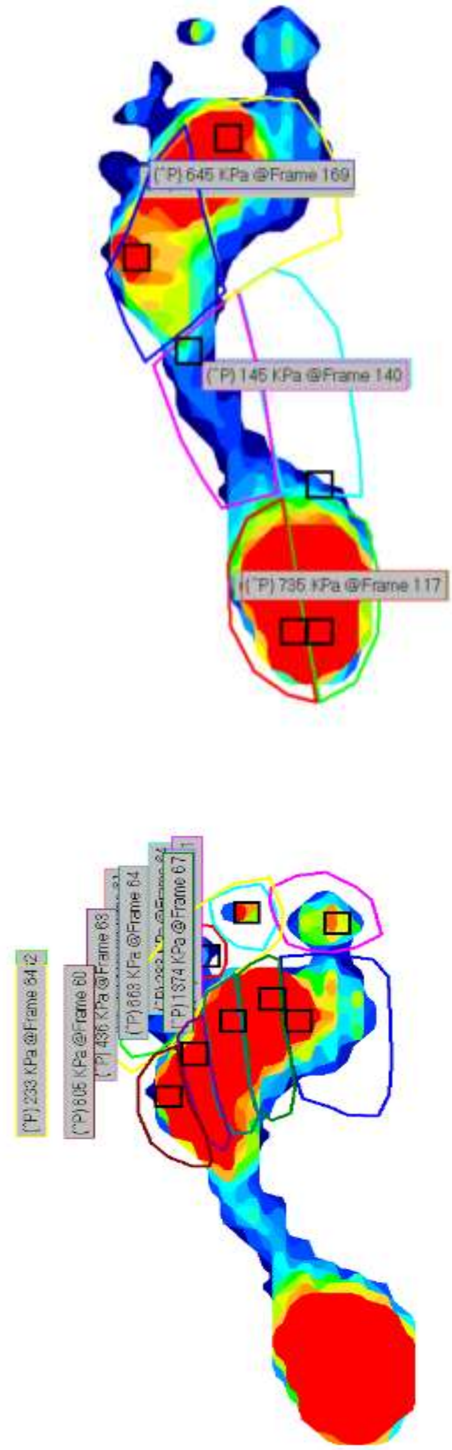

Figure 5.2: Plantar pedobarographic images for older adult subject showing 15 selected plantar regions, namely the medial heel, lateral heel, medial mid-foot, lateral mid-foot, medial forefoot, lateral forefoot, metatarsal (1, 2, 3, 4, and 5), and toe (1, 2, 3, 4, and 5).

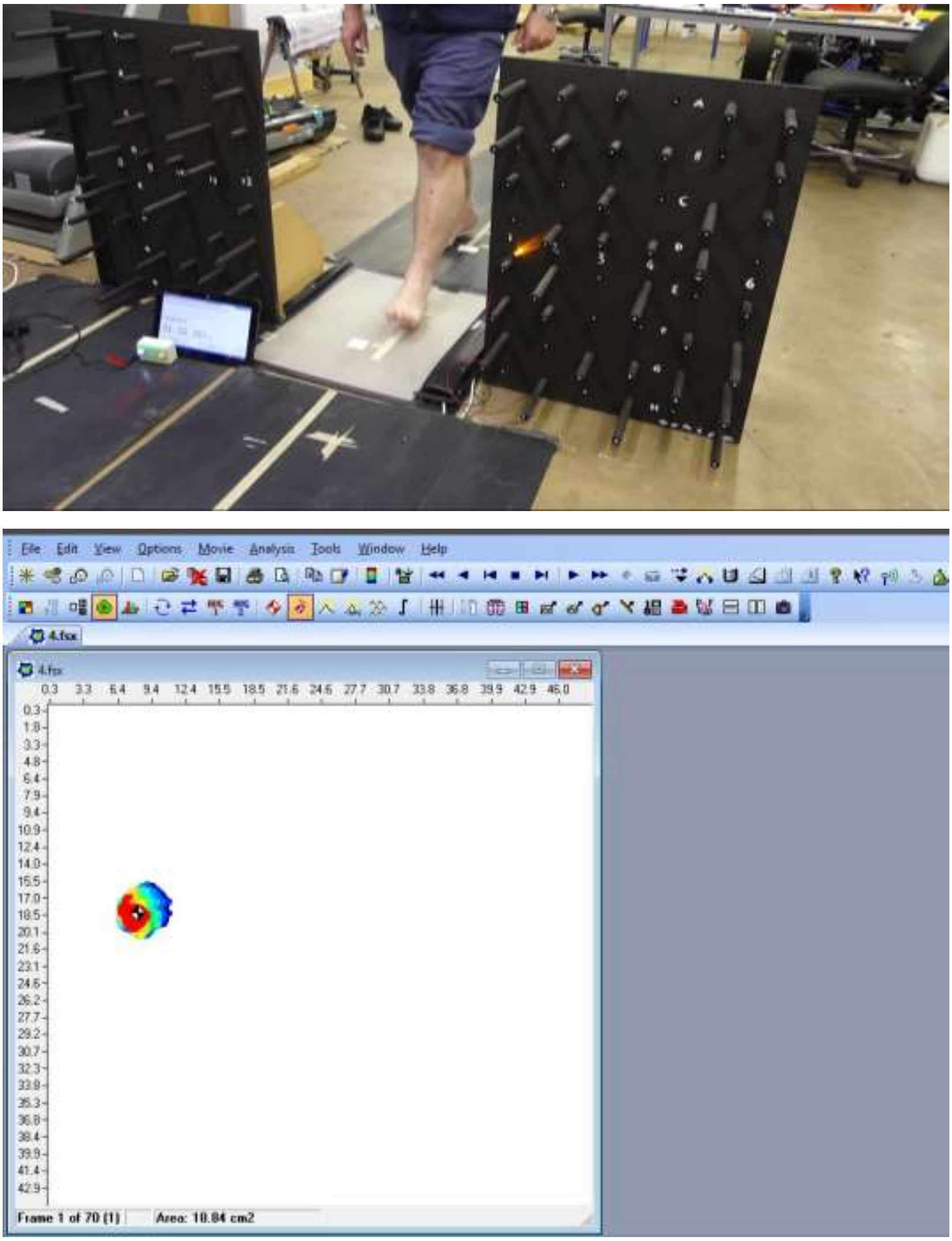

Figure 5.3: Image of the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at heel-strike phase.

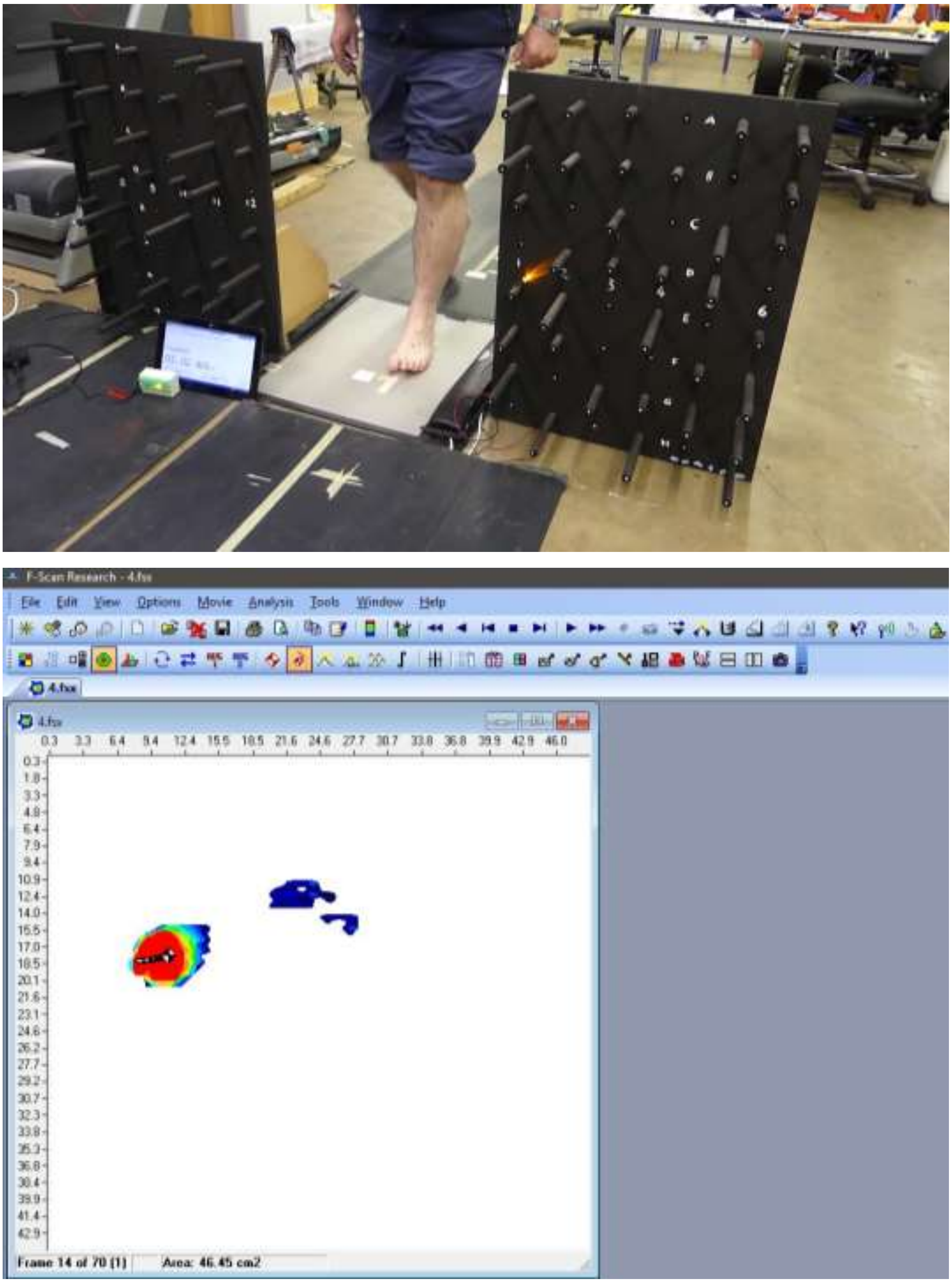

Figure 5.4: Image of the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at foot-flat phase.

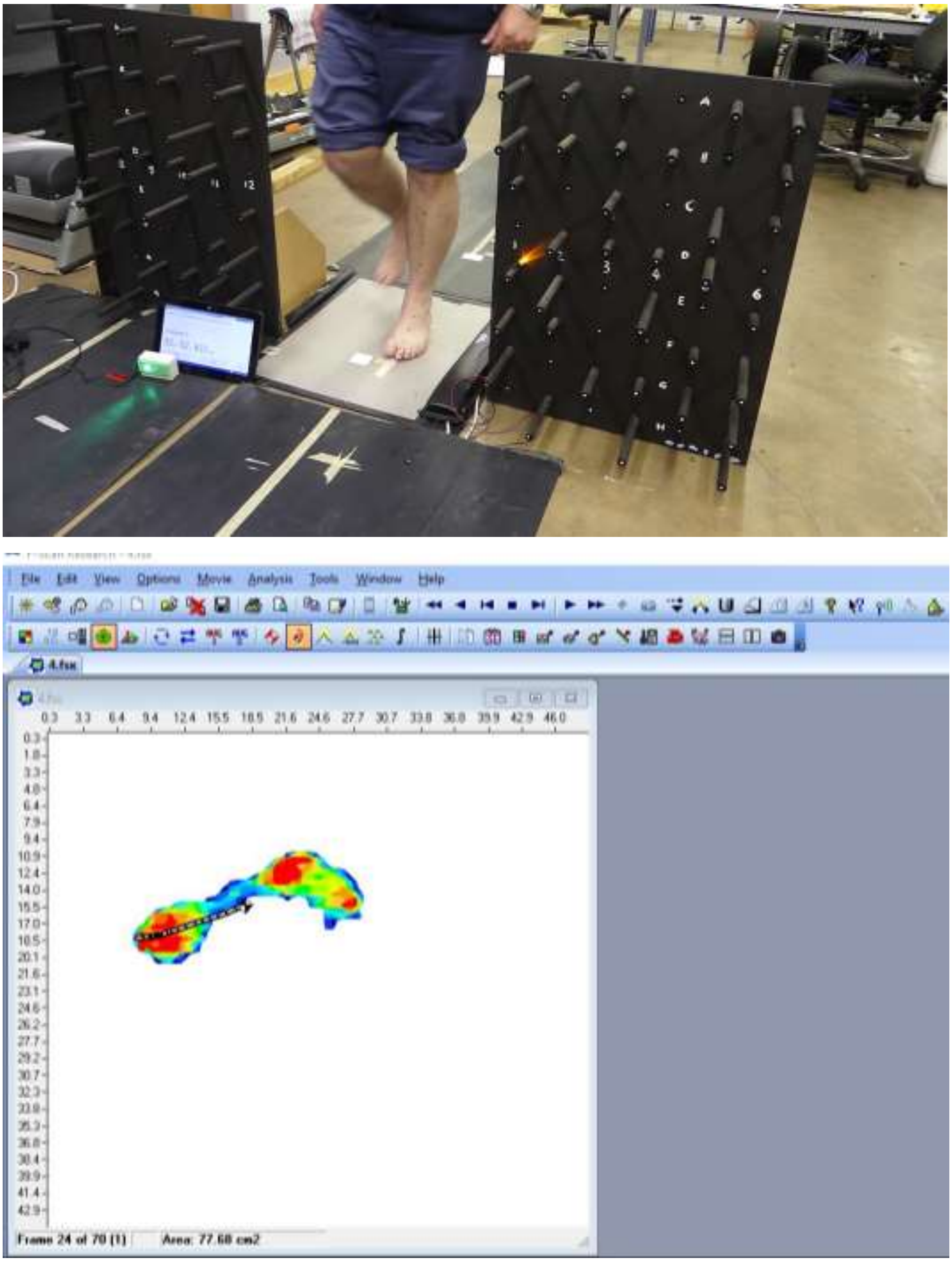

Figure 5.5: Image of the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at mid-stance phase.

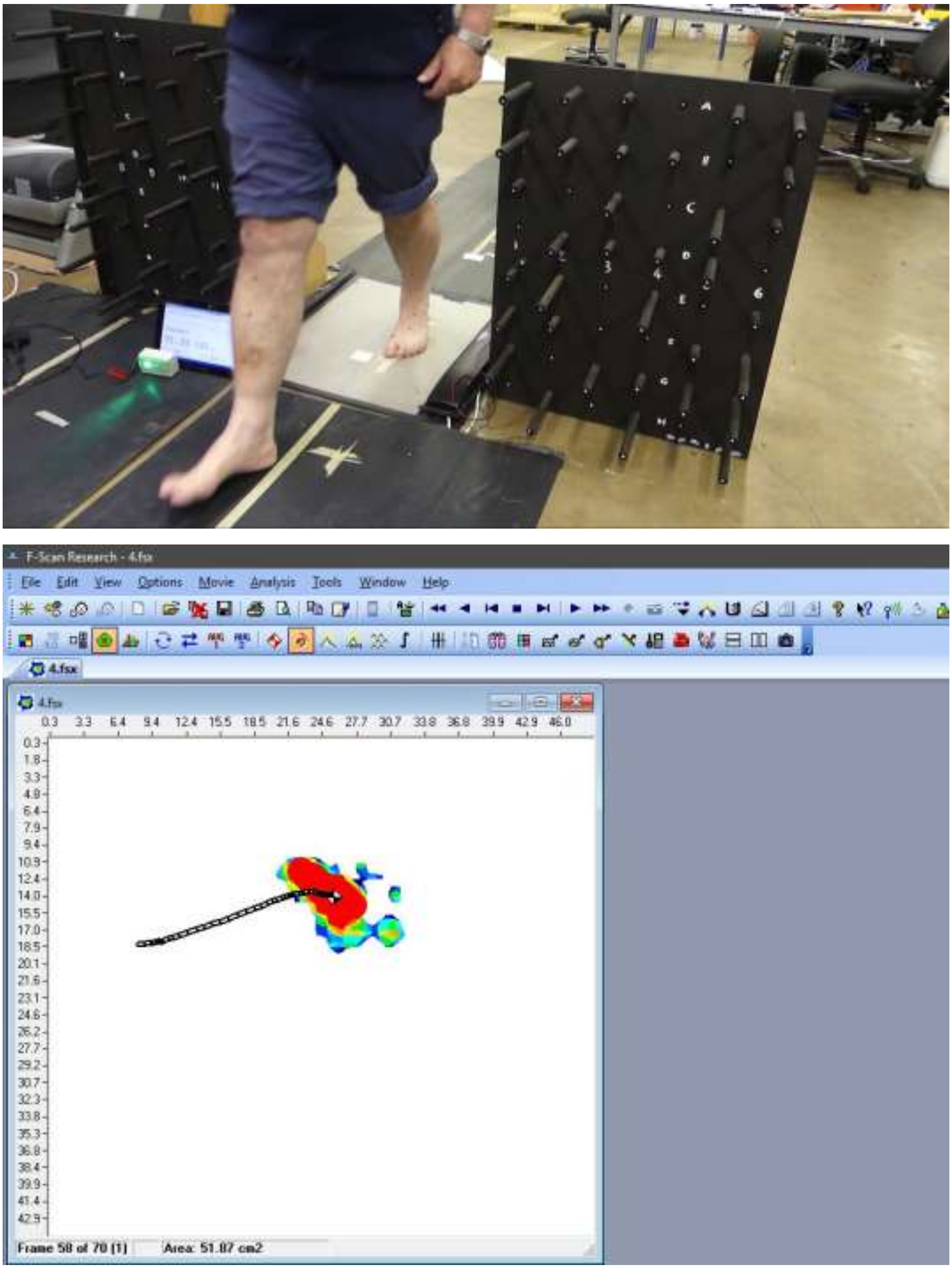

Figure 5.6: Image of the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at push-down phase.

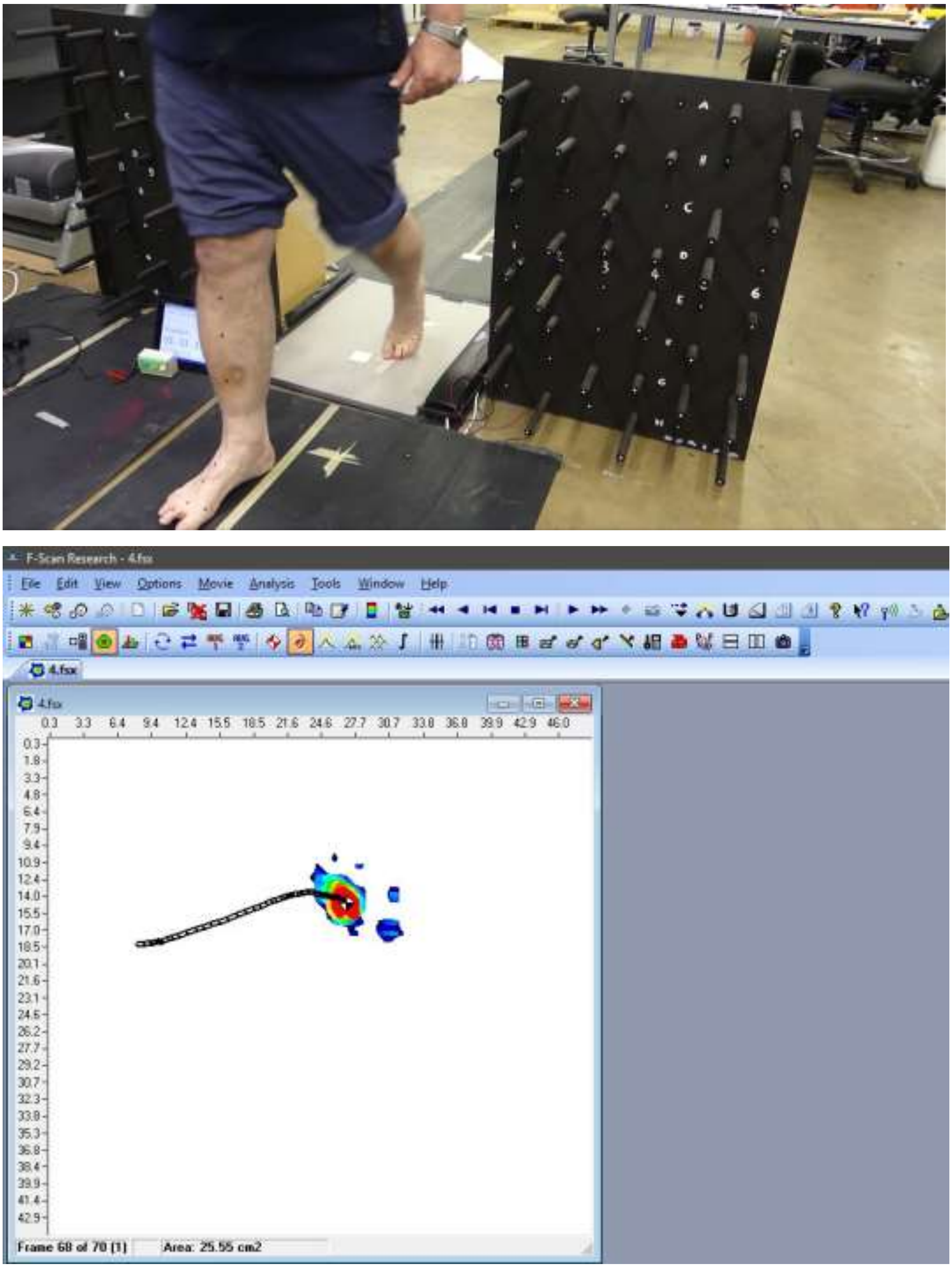

Figure 5.7: Image of the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at toe-off phase.

5.4 Plantar pressure characteristics results for the five loading phases of the gait

During the initial contact (IC) phase, the results revealed lower plantar pressure values for older adult participants compared with the adults' group beneath both medial heel and lateral heel regions while the subjects walked barefooted. The smaller measures in plantar pressure measurements included the contact pressure, and peak pressure values under the medial and lateral heel areas for the older adults' group. The mean contact pressures at medial and lateral heel regions were (medial heel: 178.04 ± 73.18, 246.66 ± 55.37 kpa), (lateral heel: 133.9 ± 57.18, 189.83 ± 58.98 kpa) for older adults and adults, respectively. Furthermore, the mean peak pressure measured under the medial and lateral heel areas were (medial heel: 431.02 ± 131.27, 529.03 ± 179.13 kpa), (lateral heel: 306.16 ± 93.95, 352.05 ± 99.23 kpa) for older adults and adults, respectively. Tables 5.1, 5.2, and 5.3 point out the comparison values between older adults and adults of contact area, contact pressure, and peak pressure parameters under barefoot walking conditions during the heel-strike phase along with the graphs, showing the mean and standard deviation values beneath the fifteen plantar regions specified in the study, as appears in Figures 5.8, 5.9, and 5.10.

Throughout the foot-flat (FF) phase, the results continued exhibiting lower values in contact pressure, and peak pressure at medial heel and lateral heel regions for older adult subjects relative to the adult subjects. Furthermore, the contact pressure measures were smaller under both medial and lateral forefoot regions during this phase for the older adults' group compared to those of the adults' group. The mean contact pressure measured under medial and lateral forefoot regions for older adults and adult subjects during the loading response phase were (medial forefoot: 39.04 ± 14.77, 46.62 ± 28.04 kpa), (lateral forefoot: 39.9 ± 15.95, 50.45 ± 15.55 kpa), respectively. The results revealed lower peak pressure values at both medial and lateral heel regions for older adult subjects compared to those of adult participants while the subjects were barefoot. In addition, the peak pressure values were smaller at metatarsal 2-5 heads and toe 2-3 regions for older adults during foot-flat phase accompanied with an increase in toe 1, and toe 4-5 regions in relation to that of adults' group results. The mean peak pressure values measured at metatarsal 2,3,4, and 5 heads for older adults group during the loading response phase were (43.8 ± 19.57, 44.99 ± 19.44, 33.15 ± 29.95, and 37.88 ± 47.49 kpa), respectively whereas these measures for adults group were (48.21 ± 25.79, 47.78 ± 44.28, 51.68 ± 24.77, and 71.44 ± 42.73 kpa), for the above four mentioned regions respectively. Tables 5.4, 5.5, and 5.6 show the mean and standard deviation values for contact area, contact pressure, and peak pressure under the fifteen foot regions during the foot-flat phase for both groups: older adult and adult. The graphs, showing the comparable values with standard deviation ranges between the two selected groups have been displayed in Figures 5.11, 5.12, and 5.13.

At the mid-stance (MS) phase, the results exhibited a number of remarkable findings. Generally, there was a noticeable difference in plantar pressure distribution between older adults and adults in most of the foot regions selected in the current work. There was a decrease in contact pressure values in medial and lateral heel regions during the mid-stance phase for older subjects compared to the adult subjects. The mean medial heel contact pressure values were (101.75 ± 37.55, 134.32 ± 29.9 kpa) for older adults and adult subjects, respectively. Similarly, the mean lateral heel contact pressure values of older and adult subjects were (82.53 ± 23.88, 110.5 ± 15.66 kpa), respectively. Furthermore, the results demonstrated that contact pressure measures were higher in mid-foot and forefoot areas, including regions under the five metatarsal heads of older people relative to adult subjects. The mean contact pressures at medial and lateral mid-foot regions were (medial mid-foot: 32.43 ± 23.2, 21.84 ± 18.62 kpa), (lateral mid-foot: 46.32 ± 26.38, 34.18 ± 19.84 kpa) for older adults and adult subjects, respectively. In addition, the mean contact pressure values under medial and lateral forefoot regions for older adults and adults were (medial forefoot: 80 ± 43.77, 59.1 ± 25.81 kpa), (lateral forefoot: 99.58 ± 54.4, 71.51 ± 11.42 kpa), respectively.

Additionally, the results pointed out an increase in contact pressure values under the hallux area for older subjects compared with the adult subjects. The mean big toe contact pressure value was (85.28 ± 52.1, 59.22 ± 62.25 kpa) for older adults and adults, respectively. Moreover, the results revealed higher values of contact pressure in the lesser-toes area for older adults relative to adult subjects, except in the region of second toe, which had a tiny amount of contact pressure when compared to the adults group. This is evident from the small magnitude of area contacted by this region for older adults group, which was only 0.03 cm^2, compared with 0.6 cm^2 as contact area value of second toe region for adults group. The mean contact pressures in the lesser-toes area were (toe 3: 49.18 ± 66.28, 20.43 ± 50.05 kpa), (toe 4,5: 43.7 ± 42.68, 33.07 ± 48.18 kpa) for older adults and adult subjects, respectively whereas the mean contact pressure under the toe 2 area for older adults and adults was (0, 43.66 ± 60.36 kpa), respectively. It is worth noting that the contact pressure in medial regions for both mid-foot and forefoot regions was lower than that in lateral regions for the two mentioned regions within the older adults' group. The mean contact pressure values for medial and lateral mid-foot regions for older adult subjects were (32.43 ± 23.2, 46.32 ± 26.38 kpa), respectively. In addition, the mean contact pressure values for medial and lateral forefoot regions within older adult participants were (80 ± 43.77, 99.58 ± 54.4 kpa), respectively.

Older adults' results showed higher peak pressure in most of the plantar regions selected in the study. However, in the heel region, including medial and lateral areas, the peak pressure recorded smaller measures for older adults when compared to adult subjects. The mean peak pressures in medial and lateral heel regions for older adults and adult subjects were (medial heel: 260.89 ± 105.27, 339.83 ± 81.56 kpa), (lateral heel: 168.39 ± 84.05, 244.13 ± 104.15 kpa), respectively. The peak pressure results were higher for older adults under medial and lateral mid-foot regions relative to adult subjects. Furthermore, the results revealed higher values of peak plantar pressure at both medial and lateral forefoot regions for older adults compared to those of the adults group. The mean peak pressures under medial and lateral forefoot regions for older adults and adults during the mid-stance phase while the subjects were under barefoot condition were (medial forefoot: 314.25 ± 150.49, 193.08 ± 70.85 kpa), (lateral forefoot: 184.67 ± 93.05, 155.65 ± 74.47 kpa), respectively. Additionally, the hallux and lesser-toes regions recorded higher values for the older adults group in relation to those measured for the adults group, except the toe 2 region, recording lower peak pressure values for older adults compared to adult subjects. The mean peak pressure for older adult group and adult group at the big toe area was (154.16 ± 162.41, 96.02 ± 149.57 kpa), respectively. Tables 5.7, 5.8, and 5.9 present the mean and standard deviation values for older adults and adult subjects for contact area, contact pressure, and peak plantar pressure during the mid-stance phase under barefoot walking conditions, along with the graphs, showing the comparisons between the two selected groups beneath the fifteen plantar regions specified in the current work as displayed in Figures 5.14, 5.15 and 5.16.

During the push-down (PD) phase, there were observationally no results to be measured in the heel and mid-foot regions, as presented in Tables 5.10, 5.11, and 5.12. These tables point out the mean and standard deviation values for older adults and adult subjects beneath a number of plantar regions specified in the study during the push-down phase while the subjects were barefoot during the gait test trials. There was a noticeable difference in plantar pressure values distributed under a number of plantar regions between the two groups during this phase, revealing higher measures for older adults group compared to those measured for adults group. The forefoot area on both sides: medial and lateral, had higher contact pressure values for older adults relative to adult subjects. The mean medial forefoot contact pressure values during the push-down phase for older adults and adult subjects were (271.99 ± 52.55, 224.94 ± 54.25 kpa), respectively. Similarly, the mean lateral forefoot contact pressure values were (184.61 ± 126.31, 109 ± 27.21 kpa), for older adults and adult subjects respectively. It is worth noting that while the lateral forefoot area exhibited higher contact pressure for older adults group, the mean contact area was lower than that recorded for adult subjects under this region. The results obtained during the mid-stance phase in terms of the contact pressure values under medial and lateral forefoot regions showed higher values at the lateral forefoot region than the medial region within older adults group. In contrast, the outcomes of contact pressure during the push-down phase exhibited higher values under the medial part of the forefoot region than that of the lateral side.

The hallux and lesser-toes regions during the push-down phase had higher contact pressure values for older adults compared to adults group, except the toe 2 region, which showed less contact pressure values for older adults group. The higher contact pressure at the hallux region for older adults was accompanied by less contact area relative to adult participants. The mean contact pressure for older adults and adults at the big toe region was (240.1 ± 100.41, 170.05 ± 102.53 kpa), respectively whilst the contact area registered (5.92 ± 0.97, 7.63 ± 1.06 cm^2), for older adults and adults respectively.

Older adults' results showed an excessive increase in peak pressure values at both medial and lateral forefoot regions during the push-down phase while the subjects were barefoot for older adults compared to adult subjects. The mean peak pressure values under medial and lateral forefoot regions were (medial forefoot: 743.03 ± 220, 556.89 ± 185.49 kpa), (lateral forefoot: 460.82 ± 163.9, 306.57 ± 91.49 kpa), for older adults and adults respectively. As previously mentioned during the push-down phase, the lateral forefoot area had lower contact area for older adults relative to adult subjects for which the values were (13.25 ± 4.89, 15.09 ± 4.39 cm^2), for the two tested groups respectively, the results revealed higher peak pressure at this region for older adults compared with the control group: the adult participants. The older adults had higher peak pressure values in their medial forefoot region than that of the lateral forefoot region during the push-down phase under barefoot gait condition. This is evident from the higher amounts of peak pressure distributed beneath the first, second, and third metatarsal heads compared to the fourth and fifth ones for which these measures were (386.95 ± 290.28, 622.73 ± 189.9, 462.17 ± 118.28, 298.41 ± 113.38, and 283.75 ± 436.46 kpa), for the above mentioned regions respectively.

While peak pressure values remained high at the hallux region during the mid-stance phase, the results kept showing an increase in peak pressures for older adults underneath this region relative to the outcomes of the adults group during the push-down phase. It is worth noting that the increase in peak pressures was accompanied with less contact area values under the hallux region for older adults compared to adult subjects. The mean big toe peak pressure was (490.81 ± 137.68, 405.44 ± 165.13 kpa), for older and adult participants respectively. Additionally, the lesser-toes region had higher peak pressure measures for older adults, except the toe 2 region, which displayed less peak pressure for older adults compared to the adults group. The mean peak pressures within the older adults group in the lesser-toes region, including toe 2, toe 3, and toe 4, 5 regions were (135.33 ± 93.58, 212.95 ± 166.47, 195.45 ± 166.98 kpa), respectively, whereas these values for adults group were (415.77 ± 224.69, 130.54 ± 99.34, 123.91 ± 109.24 kpa), respectively. The comparison graphs between the two groups selected in the study: older adults and adult subjects during the push-down phase in the fifteen foot regions to display contact area, contact pressure, and peak pressure parameters have been presented in Figures 5.17, 5.18, and 5.19.

Throughout the toe-off (TO) phase of the gait cycle, the results have been obtained from only the forefoot region, with fewer readings beneath the metatarsal heads compared with the push-down phase. That can be seen from the distributed contact area, contact pressure, and peak pressure mean and standard deviation values during the toe-off phase for both older and adult subjects shown in Tables 5.13, 5.14, and 5.15. The results continued showing higher contact pressure values at both medial and lateral forefoot regions during this phase for older adults compared to adult participants. The mean medial forefoot contact pressure value for older adults and adults was (84.93 ± 105.35, 42.79 ± 68.28 kpa), respectively. Similarly, the contact pressure at the lateral forefoot region was (28.09 ± 54.12, 19.9 ± 31.79 kpa), for older adult and adult groups respectively. Furthermore, the results revealed higher values of peak pressure at the forefoot region, particularly under the medial part of that region, recording values of (207.18 ± 219.19, 95.92 ± 152.21 kpa), for older adults and adult subjects respectively. This is also evident from the noticeable difference in peak pressure measured at first, second, and third metatarsal heads between the two groups who participated in the study. Beyond this, the larger difference in the three above mentioned regions between older adults and adult subjects was specifically located at the region of second metatarsal head with peak pressure value of (204.81 ± 140.59, 96.09 ± 152.54 kpa), for older and adult subjects, respectively.

Importantly, the hallux area recorded higher peak pressure for older adults compared to adult subjects with measured values of (358.34 ± 180.25, 298.06 ± 165.83 kpa), respectively. The increase in peak pressure values at the hallux region was accompanied by lower contact area values for older adults relative to adults group. The contact area variable at the hallux region recorded (3.76 ± 2.19, 6.6 ± 0.6 cm^2), for older adults and adult participants respectively. In addition, there was an increase in peak pressure values for older adults in the lesser-toes region during the toe-off phase compared to adults group except the toe 2 region, which has smaller values for the older adults group. The mean peak pressure values in the lesser-toes area for older adults, comprising toe 2, toe 3, and toe 4, 5 regions were (88.41 ± 37.86, 108.72 ± 83.96, 83.44 ± 97.53 kpa), respectively while these values for adult subjects measured at the three above regions were (194.6 ± 122.2, 50.04 ± 48.88, 18.07 ± 28.38 kpa), respectively. Figures 5.20, 5.21, and 5.22 point out the comparison graphs between the two groups selected in the study: older adults and adult subjects during the toe-off of the stance phase of the gait cycle under the specified fifteen foot regions for the contact area, contact pressure, and peak pressure distribution measurements.

Table 5.1: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of three walking trials for each subject in 15 selected regions at heel-strike phase.

Contact Area	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	10.22	1.36	10.12	2.88
Lateral Heel	7.59	2.25	7.46	2.31
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	0	0	0	0
Lateral Forefoot	0	0	0	0
Metatarsal 1	0	0	0	0
Metatarsal 2	0	0	0	0
Metatarsal 3	0	0	0	0
Metatarsal 4	0	0	0	0
Metatarsal 5	0	0	0	0
Toe 1	0	0	0	0
Toe 2	0	0	0	0
Toe 3	0	0	0	0
Toe 4,5	0	0	0	0

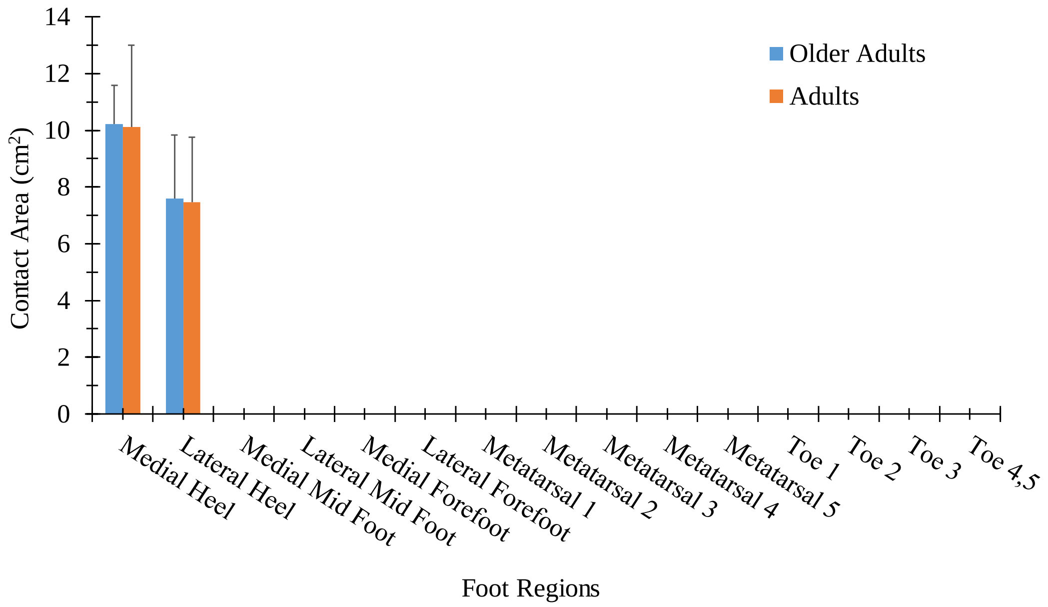

Figure 5.8: Mean and standard deviation of contact area values in (cm^2) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during heel-strike phase.

Table 5.2: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at heel-strike phase.

Contact Pressure	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	178.04	73.18	246.66	55.37
Lateral Heel	133.90	57.18	189.83	58.98
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	0	0	0	0
Lateral Forefoot	0	0	0	0
Metatarsal 1	0	0	0	0
Metatarsal 2	0	0	0	0
Metatarsal 3	0	0	0	0
Metatarsal 4	0	0	0	0
Metatarsal 5	0	0	0	0
Toe 1	0	0	0	0
Toe 2	0	0	0	0
Toe 3	0	0	0	0
Toe 4,5	0	0	0	0

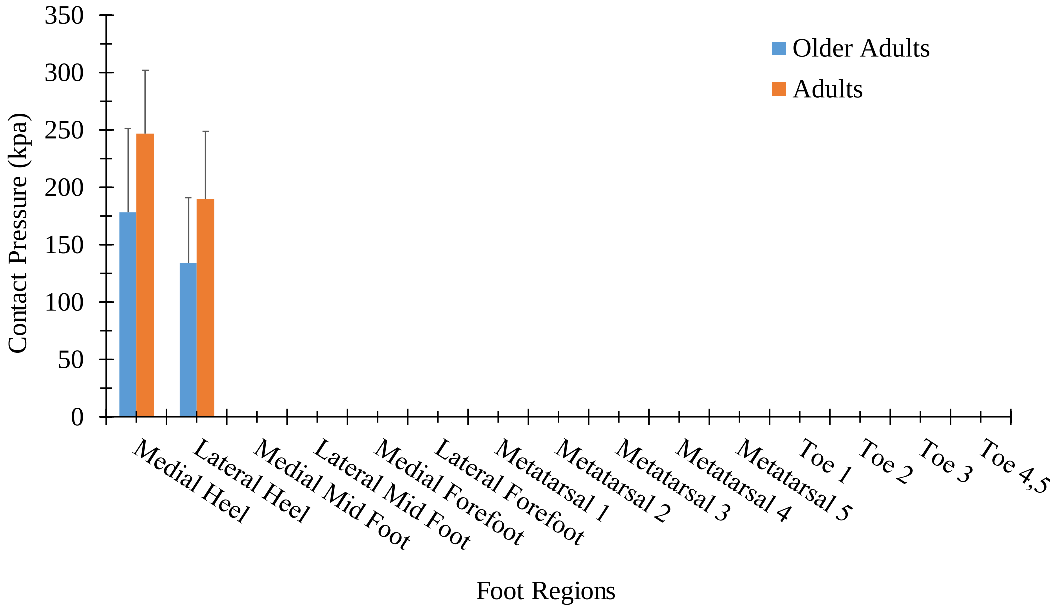

Figure 5.9: Mean and standard deviation of contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during heel-strike phase.

Table 5.3: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at heel-strike phase.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	431.02	131.27	529.03	179.13
Lateral Heel	306.16	93.95	352.05	99.23
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	0	0	0	0
Lateral Forefoot	0	0	0	0
Metatarsal 1	0	0	0	0
Metatarsal 2	0	0	0	0
Metatarsal 3	0	0	0	0
Metatarsal 4	0	0	0	0
Metatarsal 5	0	0	0	0
Toe 1	0	0	0	0
Toe 2	0	0	0	0
Toe 3	0	0	0	0
Toe 4,5	0	0	0	0

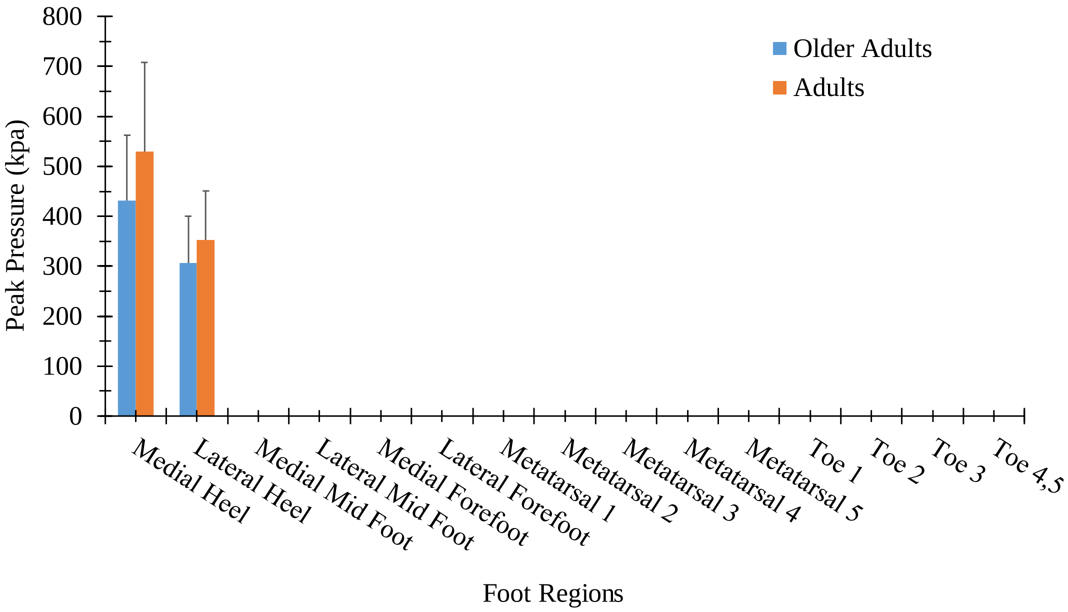

Figure 5.10: Mean and standard deviation of peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during heel-strike phase.

Table 5.4: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of three walking trials for each subject in 15 selected regions at foot-flat phase.

Contact Area	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	15.11	2.05	14.10	1.44
Lateral Heel	11.67	1.47	11.53	1.77
Medial Mid Foot	0.48	0.61	0.04	0.11
Lateral Mid Foot	2.03	2.16	4.03	4.85
Medial Forefoot	5.53	2.75	2.40	1.42
Lateral Forefoot	7.49	6.23	7.46	5.75
Metatarsal 1	1.35	1.79	0.51	0.81
Metatarsal 2	2.38	1.12	1.28	1.11
Metatarsal 3	2.93	1.47	1.85	1.71
Metatarsal 4	2.99	2.52	2.44	2.14
Metatarsal 5	3.25	4.04	7.38	5.05
Toe 1	0.35	0.74	0	0
Toe 2	0	0	0.17	0.42
Toe 3	0	0	0.09	0.21
Toe 4,5	0.26	0.73	0	0

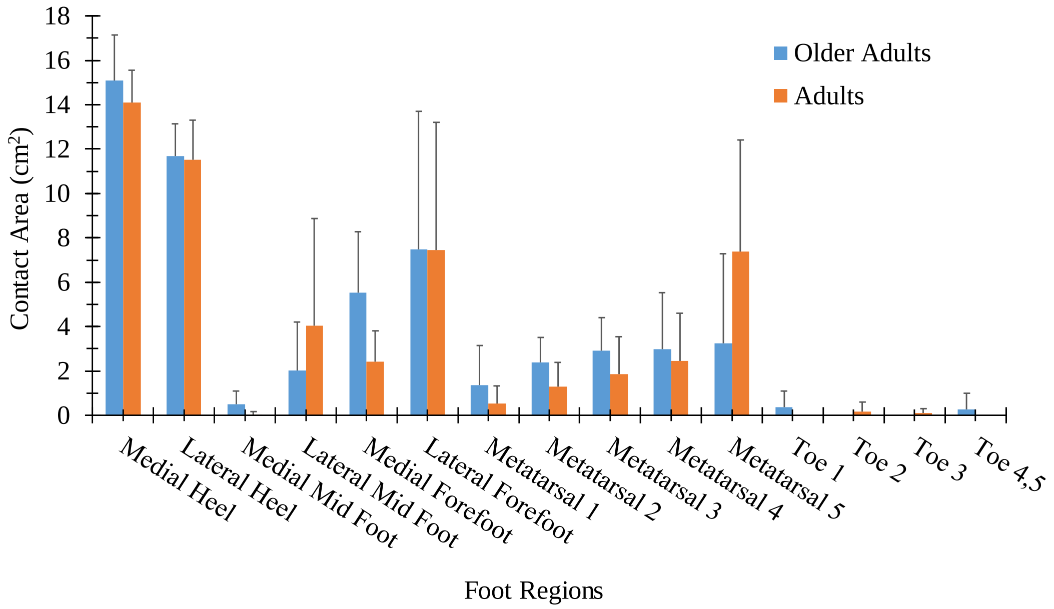

Figure 5.11: Mean and standard deviation of contact area values in (cm^2) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during foot-flat phase.

Table 5.5: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at foot-flat phase.

Contact Pressure	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	286.87	98.55	302.16	50.78
Lateral Heel	233.45	75.66	239.25	30.42
Medial Mid Foot	21.82	27.67	9.43	23.11
Lateral Mid Foot	31.60	24.56	32.41	24.14
Medial Forefoot	39.04	14.77	46.62	28.04
Lateral Forefoot	39.90	15.95	50.45	15.55
Metatarsal 1	26.78	24.45	24.33	38.35
Metatarsal 2	38.02	17.41	51.26	33.74
Metatarsal 3	39.71	15.90	44.49	21.32
Metatarsal 4	27.92	20.50	44.24	15.68
Metatarsal 5	29.46	28.85	38.59	22.38
Toe 1	12.50	24.01	0	0
Toe 2	0	0	24.61	60.28
Toe 3	0	0	14.15	34.66
Toe 4,5	10.72	30.31	0	0

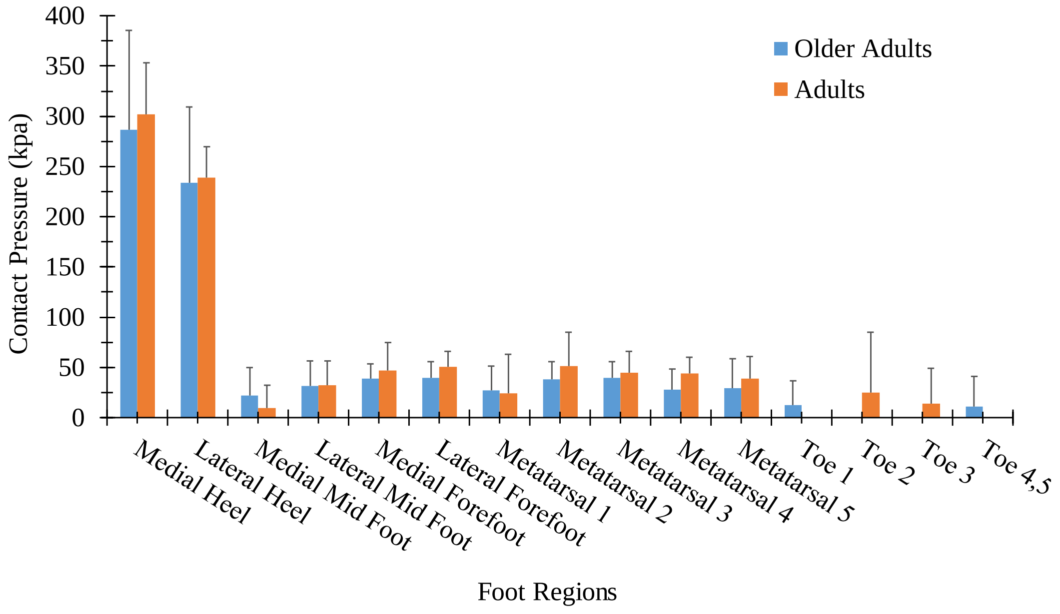

Figure 5.12: Mean and standard deviation of contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during foot-flat phase.

Table 5.6: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at foot-flat phase.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	719.79	210.81	765.93	171.17
Lateral Heel	442.76	174.69	571.11	155.71
Medial Mid Foot	16.57	26.18	4.74	11.60
Lateral Mid Foot	34.33	38.53	52.16	50.64
Medial Forefoot	59.19	34.24	59.56	35.89
Lateral Forefoot	54.46	41.67	79.17	35.45
Metatarsal 1	26.04	39.13	23.50	37.55
Metatarsal 2	43.80	19.57	48.21	25.79
Metatarsal 3	44.99	19.44	47.78	44.28
Metatarsal 4	33.15	29.95	51.68	24.77
Metatarsal 5	37.88	47.49	71.44	42.73
Toe 1	14.21	30.37	0	0
Toe 2	0	0	42.62	104.39
Toe 3	0	0	14.21	34.80
Toe 4,5	15.39	43.53	0	0

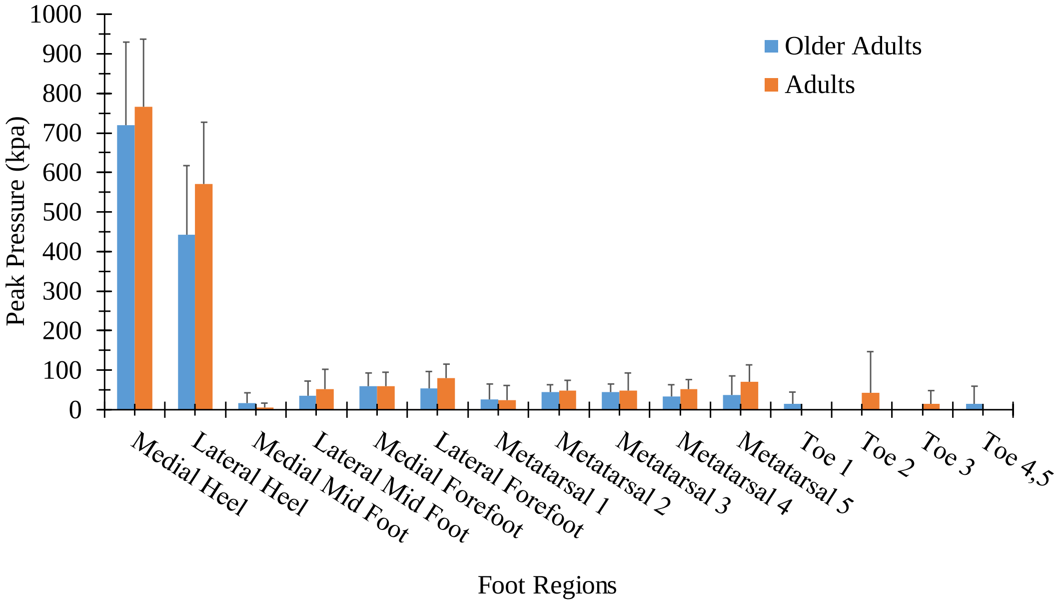

Figure 5.13: Mean and standard deviation of peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during foot-flat phase.

Table 5.7: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of three walking trials for each subject in 15 selected regions at mid-stance phase.

Contact Area	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	13.85	1.85	13.10	2.38
Lateral Heel	9.47	1.58	9.83	2.02
Medial Mid Foot	0.90	1.38	0.22	0.20
Lateral Mid Foot	4.73	5.20	7.99	8.32
Medial Forefoot	16.55	3.60	11.68	3.09
Lateral Forefoot	14.91	8.25	13.65	3.51
Metatarsal 1	7.18	3.18	4.77	2.87
Metatarsal 2	6.09	2.04	4.34	1.07
Metatarsal 3	6.47	2.01	5.41	0.61
Metatarsal 4	6.05	1.64	5.54	1.42
Metatarsal 5	4.96	4.13	12.58	5.90
Toe 1	1.74	1.66	1.37	1.90
Toe 2	0.03	0.09	0.60	0.68
Toe 3	0.58	0.69	0.09	0.21
Toe 4,5	1.26	1.42	0.60	0.78

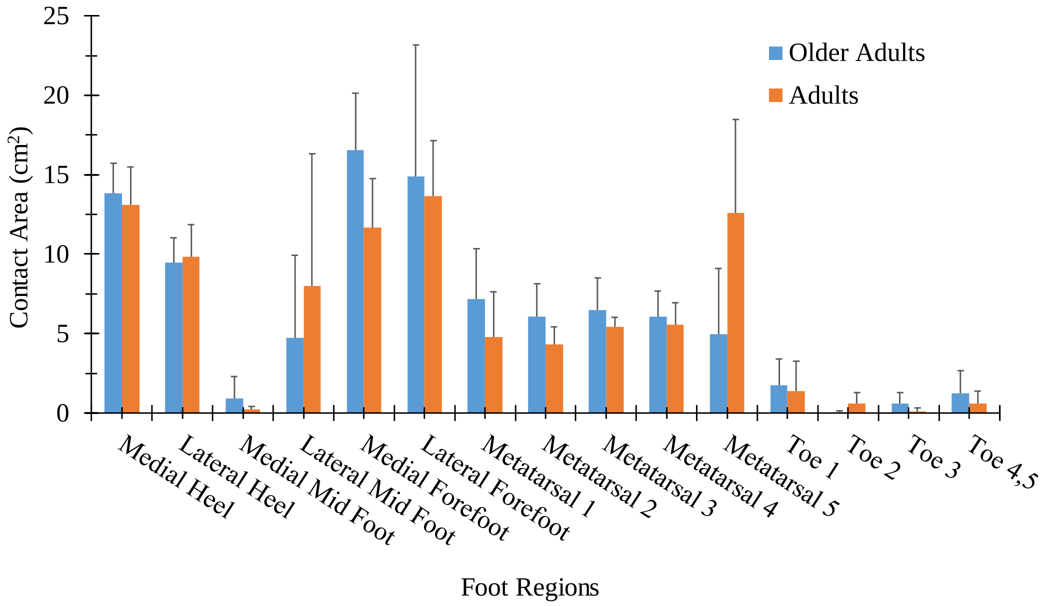

Figure 5.14: Mean and standard deviation of contact area values in (cm^2) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

Table 5.8: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at mid-stance phase.

Contact Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	101.75	37.55	134.32	29.90
Lateral Heel	82.53	23.88	110.50	15.66
Medial Mid Foot	32.43	23.20	21.84	18.62
Lateral Mid Foot	46.32	26.38	34.18	19.84
Medial Forefoot	80.00	43.77	59.06	25.81
Lateral Forefoot	99.58	54.40	71.51	11.42
Metatarsal 1	83.66	74.00	56.06	30.33
Metatarsal 2	104.76	38.37	83.19	25.74
Metatarsal 3	102.51	40.68	73.53	22.33
Metatarsal 4	79.30	60.51	68.80	9.03
Metatarsal 5	68.50	74.03	64.40	11.32
Toe 1	85.28	52.10	59.22	62.25
Toe 2	0	0	43.66	60.36
Toe 3	49.18	66.28	20.43	50.05
Toe 4,5	43.69	42.68	33.07	48.18

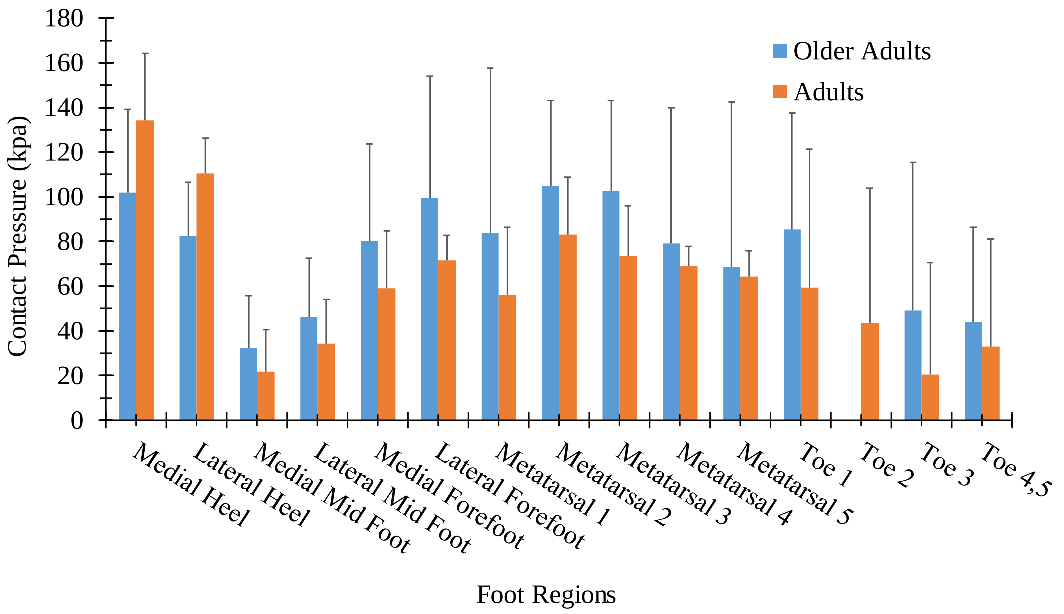

Figure 5.15: Mean and standard deviation of contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

Table 5.9: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at mid-stance phase.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	260.89	105.27	339.83	81.56
Lateral Heel	168.39	84.05	244.13	104.15
Medial Mid Foot	30.16	19.92	11.92	13.95
Lateral Mid Foot	104.55	71.49	76.27	76.96
Medial Forefoot	314.25	150.49	193.08	70.85
Lateral Forefoot	184.67	93.05	155.65	74.47
Metatarsal 1	227.68	179.10	99.71	68.52
Metatarsal 2	225.50	72.25	165.00	78.29
Metatarsal 3	158.23	54.60	141.68	92.58
Metatarsal 4	145.03	92.32	126.32	57.49
Metatarsal 5	99.61	109.58	137.47	53.05
Toe 1	154.16	162.41	96.02	149.57
Toe 2	0	0	96.56	157.83
Toe 3	54.55	79.01	20.55	50.35
Toe 4,5	68.78	85.27	42.44	56.60

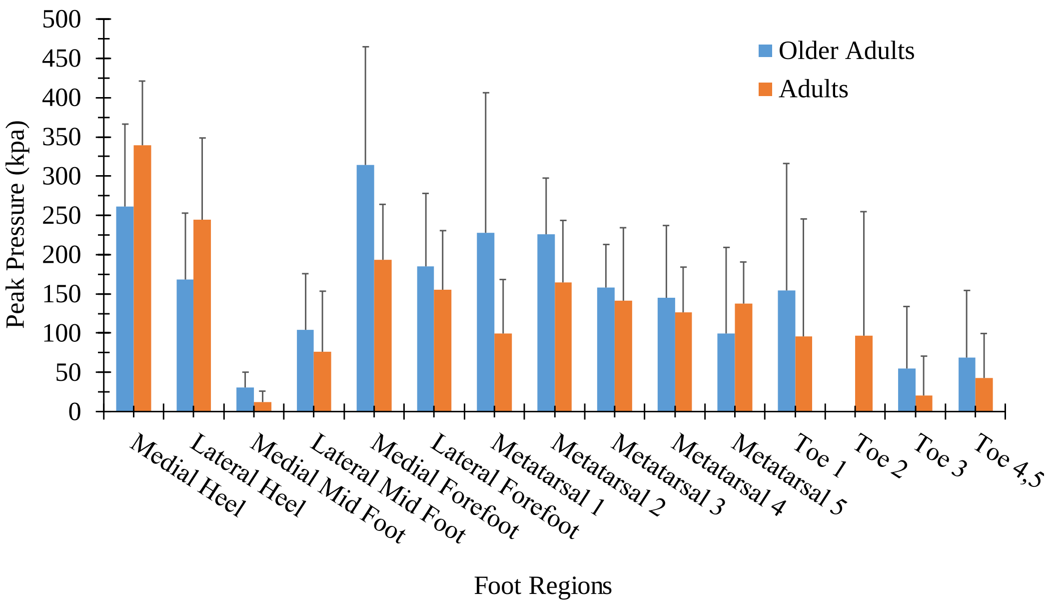

Figure 5.16: Mean and standard deviation of peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

Table 5.10: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of three walking trials for each subject in 15 selected regions at push-down phase.

Contact Area	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0.09	0.21
Medial Forefoot	19.16	3.72	17.66	3.77
Lateral Forefoot	13.25	4.89	15.09	4.39
Metatarsal 1	9.45	3.48	9.09	2.02
Metatarsal 2	6.53	1.83	5.70	1.02
Metatarsal 3	6.66	1.50	5.75	0.77
Metatarsal 4	5.79	0.62	5.49	1.54
Metatarsal 5	3.60	1.82	6.77	3.35
Toe 1	5.92	0.97	7.63	1.06
Toe 2	1.77	0.62	2.79	0.53
Toe 3	1.77	0.97	1.67	1.03
Toe 4,5	3.02	1.81	1.84	1.19

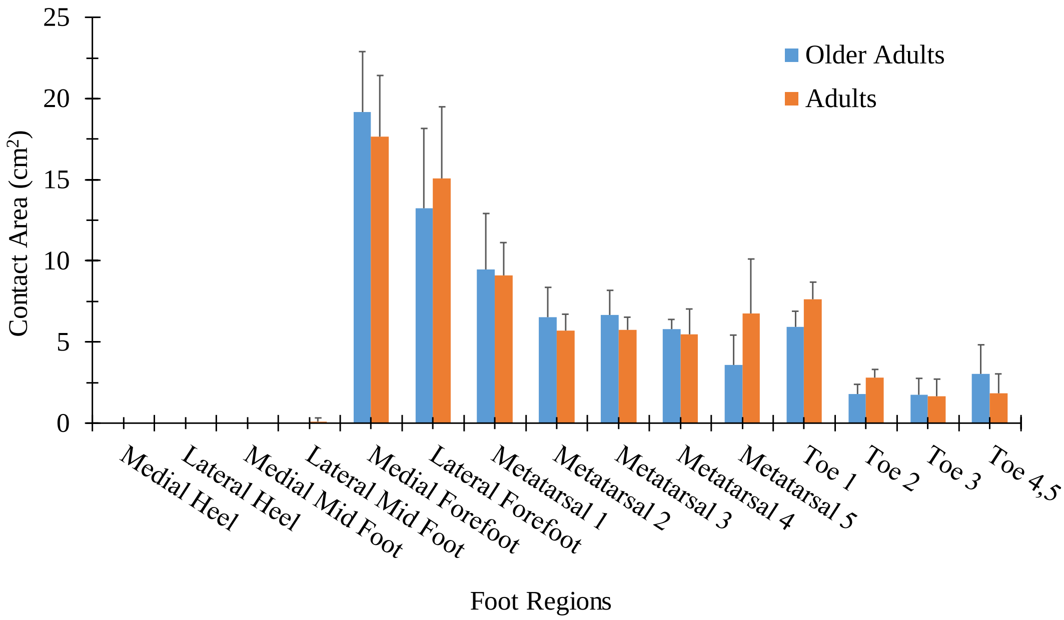

Figure 5.17: Mean and standard deviation of contact area values in (cm^2) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during push-down phase.

Table 5.11: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at push-down phase.

Contact Pressure	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	6.29	15.40
Medial Forefoot	271.99	52.55	224.94	54.25
Lateral Forefoot	184.61	126.31	109.00	27.21
Metatarsal 1	199.30	75.68	152.53	32.32
Metatarsal 2	331.59	61.61	211.57	55.35
Metatarsal 3	286.40	92.12	202.76	51.39
Metatarsal 4	172.47	115.90	140.37	47.31
Metatarsal 5	136.94	163.40	101.15	47.50
Toe 1	240.10	100.41	170.05	102.53
Toe 2	68.13	47.88	204.60	108.62
Toe 3	144.40	110.54	94.90	70.05
Toe 4,5	119.06	82.00	98.16	79.55

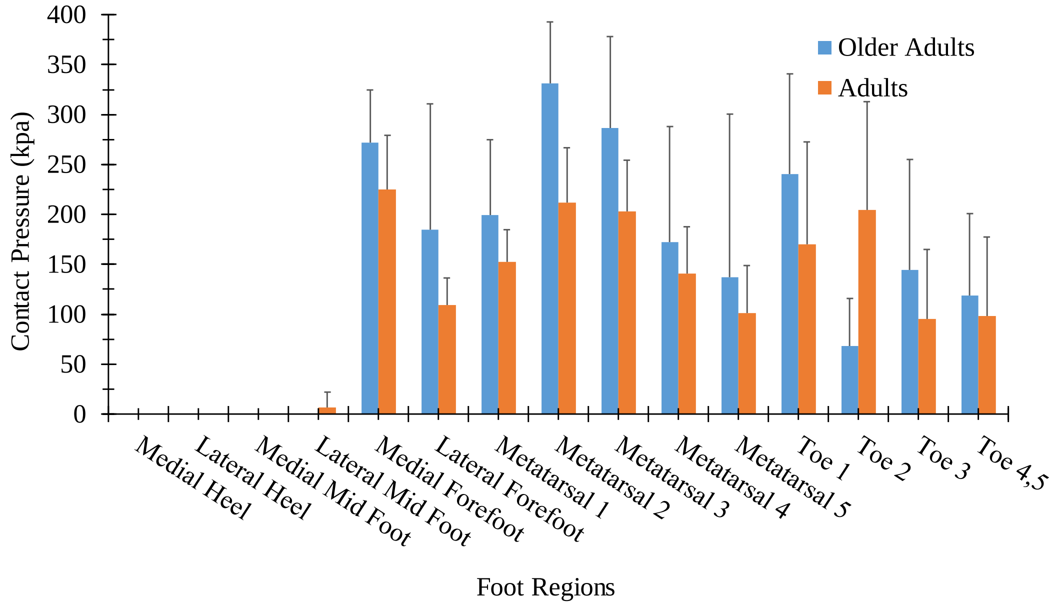

Figure 5.18: Mean and standard deviation of contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during push-down phase.

Table 5.12: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at push-down phase.

Peak Pressure	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	3.16	7.73
Medial Forefoot	743.03	220.00	556.89	185.49
Lateral Forefoot	460.82	163.90	306.57	91.49
Metatarsal 1	386.95	290.28	343.32	138.05
Metatarsal 2	622.73	189.90	529.42	191.44
Metatarsal 3	462.17	118.28	405.99	96.31
Metatarsal 4	298.41	113.38	243.32	64.17
Metatarsal 5	283.75	436.46	251.93	126.62
Toe 1	490.81	137.68	405.44	165.13
Toe 2	135.33	93.58	415.77	224.69
Toe 3	212.95	166.47	130.54	99.34
Toe 4,5	195.45	166.98	123.91	109.24

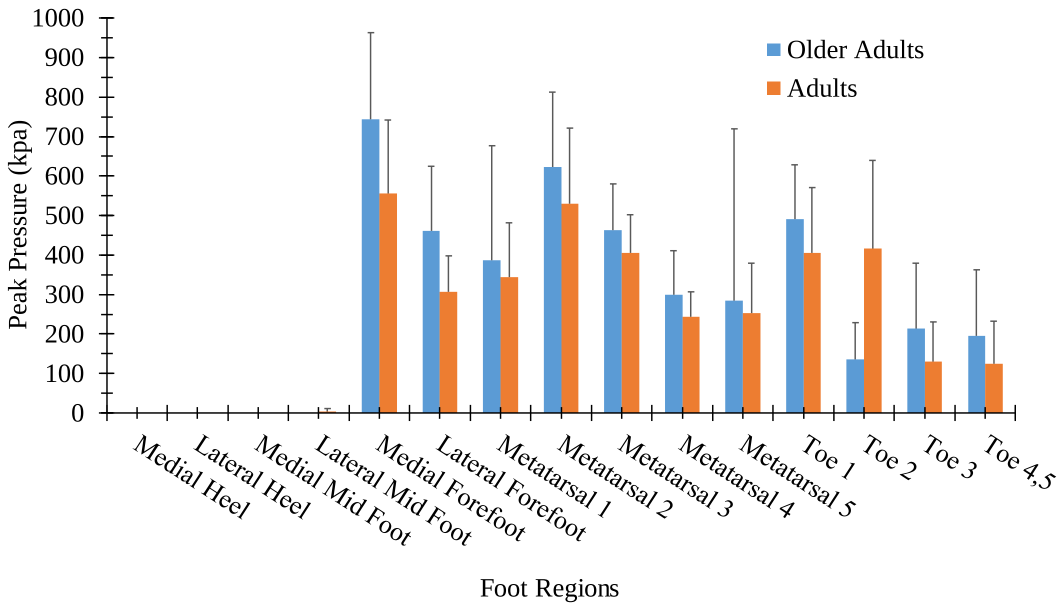

Figure 5.19: Mean and standard deviation of peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during push-down phase.

Table 5.13: Mean values and standard deviations for contact area in (cm^2) for older adult and adult groups of three walking trials for each subject in 15 selected regions at toe-off phase.

Contact Area	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	1.93	3.21	1.89	3.03
Lateral Forefoot	1.29	2.52	0.73	1.66
Metatarsal 1	0.29	0.72	0.34	0.72
Metatarsal 2	1.32	2.38	1.11	1.79
Metatarsal 3	1.19	2.16	0.86	1.37
Metatarsal 4	0.32	0.81	0.34	0.84
Metatarsal 5	0	0	0	0
Toe 1	3.76	2.19	6.60	0.60
Toe 2	1.22	0.45	1.93	0.90
Toe 3	0.83	0.51	0.90	0.89
Toe 4,5	1.19	1.24	0.47	0.77

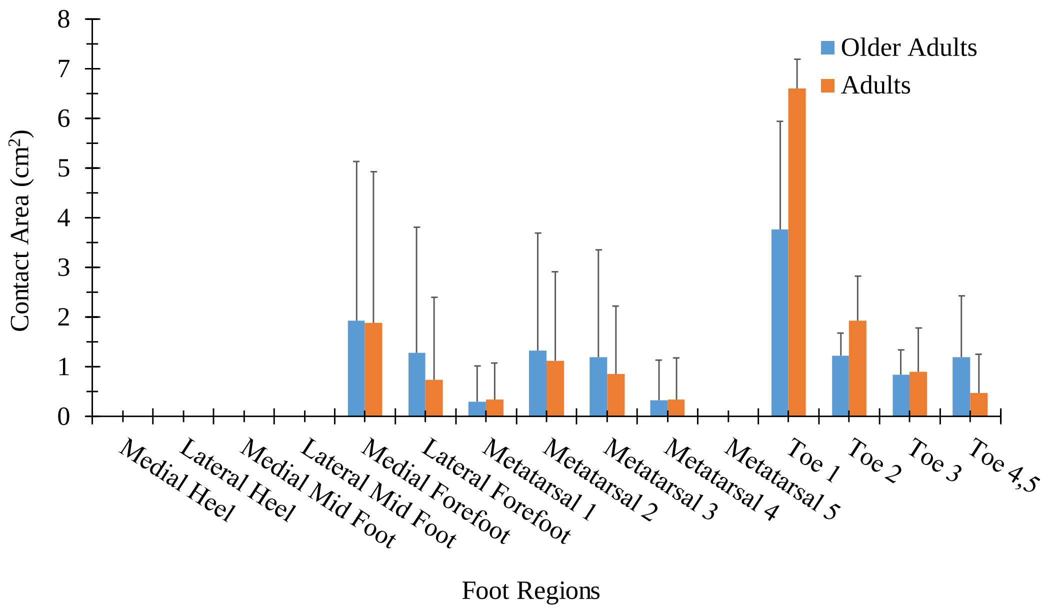

Figure 5.20: Mean and standard deviation of contact area values in (cm^2) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during toe-off phase.

Table 5.14: Mean values and standard deviations for contact pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at toe-off phase.

Contact Pressure	Older Adults		Adults	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	84.93	105.35	42.79	68.28
Lateral Forefoot	28.09	54.12	19.90	31.79
Metatarsal 1	40.31	74.84	11.38	18.08
Metatarsal 2	97.48	110.31	56.67	89.50
Metatarsal 3	35.21	59.06	25.65	40.64
Metatarsal 4	17.41	36.46	5.54	13.57
Metatarsal 5	0	0	0	0
Toe 1	182.11	113.81	159.43	79.27
Toe 2	79.94	24.47	142.08	72.04
Toe 3	122.08	69.43	49.61	43.01
Toe 4,5	72.35	67.09	15.88	26.21

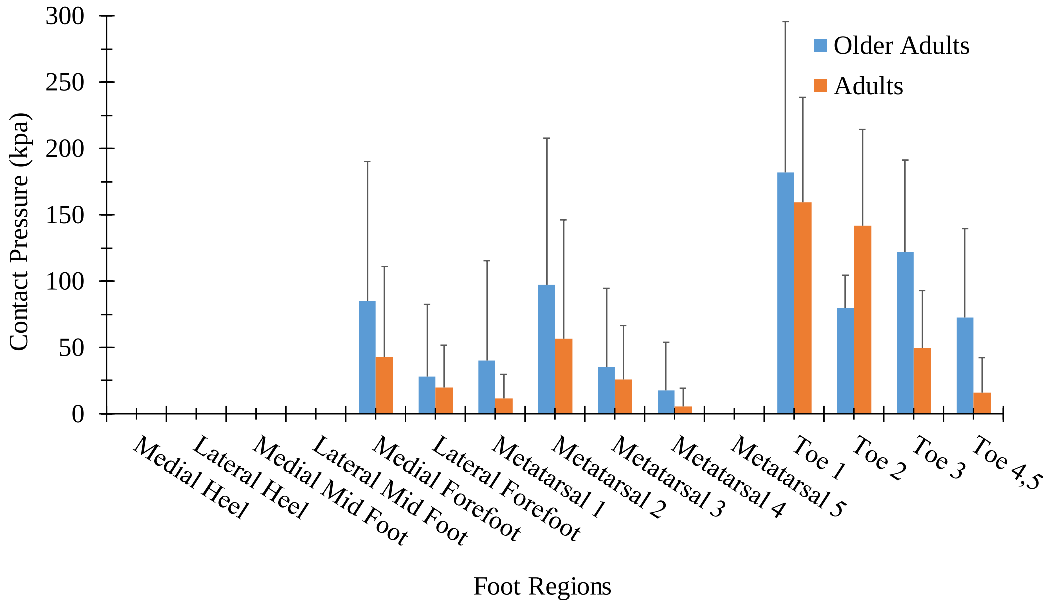

Figure 5.21: Mean and standard deviation of contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during toe-off phase.

Table 5.15: Mean values and standard deviations for peak pressure in (kpa) for older adult and adult groups of three walking trials for each subject in 15 selected regions at toe-off phase.

Peak Pressure	**Older Adults**		**Adults**	
	Mean	SD	Mean	SD
Medial Heel	0	0	0	0
Lateral Heel	0	0	0	0
Medial Mid Foot	0	0	0	0
Lateral Mid Foot	0	0	0	0
Medial Forefoot	207.18	219.19	95.92	152.21
Lateral Forefoot	46.17	91.61	14.46	27.21
Metatarsal 1	33.15	79.56	6.51	11.92
Metatarsal 2	204.81	140.59	96.09	152.54
Metatarsal 3	47.35	90.98	33.04	51.28
Metatarsal 4	16.57	43.18	6.48	15.87
Metatarsal 5	0	0	0	0
Toe 1	358.34	180.25	298.06	165.83
Toe 2	88.41	37.86	194.60	122.20
Toe 3	108.72	83.96	50.04	48.88
Toe 4,5	83.44	97.53	18.07	28.38

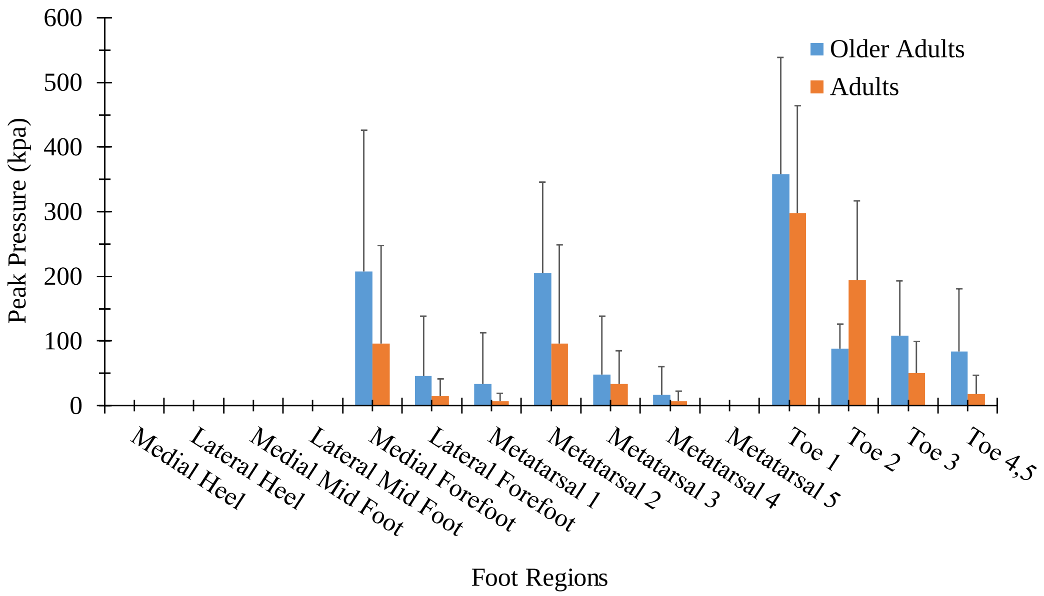

Figure 5.22: Mean and standard deviation of peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during toe-off phase.

5.5 Discussion

Barefoot plantar pressures measured under dynamic conditions have been utilised as way to evaluate the gait characteristics in older adults, as elevated plantar pressure seems to be the major risk factor of the development of foot and gait injuries. Foot injuries are the leading cause of foot complaints encountered by older people during the loading phase of gait (Burnfield et al., 2004; Bus and de Lange, 2005). The results of three repeated trials were collected for all selected subjects to obtain a reliable estimate of the actual values of contact area, contact pressure, and peak pressure for both cohorts: older adults, and adults as a control data. Three trials as gait test measurements were found to be sufficient to obtain the reliability necessary for clinical aspects in line with previous studies (Hughes et al., 1991; van der Leeden et al., 2004; Zammit et al., 2010). The subjects were requested to perform a two-step gait protocol (Bus and de Lange, 2005) to measure their plantar pressure parameters in fifteen plantar regions. The research aimed firstly to examine the variability in plantar pressure and peak plantar pressure values of a number of plantar regions covering the whole foot plantar surface during the five loading phases of the gait: the heel-strike, foot-flat, mid-stance, push-down, and toe-off to compare older adults and adult subjects. Furthermore, the research examined the variation in subjects' weight and contact time during the stance phase, in which the foot was in contact with the ground during the entire period. It aimed to understand whether this variation influenced the differences in plantar pressure and peak plantar pressure values between the two cohorts. These were compared with un-normalised plantar pressures and peak plantar pressures, specifically during the mid-stance phase when one limb was responsible for supporting human body weight. This work will be presented in the case study provided in section 5.6.

The plantar pressure parameters were measured for analysis during the main loading phases of the gait. There was a need to examine the changes in loading patterns of the human foot with advancing age during the stance phase of the gait. This investigation helped to discover the phases which are most likely to be associated with foot complaints and the development of plantar tissue injuries, leading to deterioration of foot functions during gait. Therefore, the study is significant for both research and clinical settings.

Initial contact is the term used to initiate the stance period of human gait cycle. The stance period commences with the first interval of double limb support, embracing a bilateral foot contact with the ground. This indicates body weight shared by both feet. The starting point of the initial contact phase is recognised by the first instant of foot contacting with the ground by heel rocker and this is why it has been given the term "Heel-strike". However, not all people have the capability to initiate ground contact with their heel area. The challenging task of this phase is to examine the instantaneous reaction of one extremity to the onset of transferring the body weight, thereby investigating the ability for preserving the body balance, particularly for older adults (Burnfield, 2010; Perry et al., 1993).

The contact pressure and peak pressure measured during heel-strike phase revealed lower values under both medial and lateral heel regions for older adults relative to the outcomes obtained from the adults group. The results were in line with the findings of a number of previous studies (Hessert et al., 2005; Scott et al., 2007). Apparently, older adults maintain the body balance during the initial contact phase, as can be seen from the poorer distribution of contact pressure and peak pressure values recorded under the heel region compared to the adults group. It appears that while one foot is in contact with the ground by the heel area during the heel-strike phase, the contralateral foot would bear the body weight on the forefoot region during the push-down phase as a way to provide the balance necessary during loading phases of the gait for older adults.

Throughout the foot-flat phase that follows the initial contact and continues until the other limb lifted from the ground, both feet are in direct contact with the ground. This phase is included in the initial double stance support interval. Previous studies indicated that double support time of the gait cycle increases with advancing age (Hollman et al., 2011; Menant et al., 2009a; Shkuratova et al., 2004). During the current loading response phase, the foot undergoes changes as the body weight is transferred to this specific limb. In addition, the heel area continues to contact the ground for the entire period of this phase (Burnfield, 2010). However, the results kept showing lower contact pressure and peak pressure values at both medial and lateral heel regions during the loading response phase for older adults compared to the adults group. These lower values may be because the other foot would be within toe-off of the stance phase of the gait cycle. Older people have a tendency to bear the body weight on their forefoot region during push-down and toe-off phases for forward progression and for safely stance phase termination (Menant et al., 2009b; Oates et al., 2010; Tirosh et al., 2005). Consequently, with advancing age, more contact pressure and peak pressure need to be exerted during these two phases (push-down and toe-off) for body balance requirements.

Older adults revealed lower contact pressure and peak pressure values beneath the medial and lateral forefoot regions with regard to the adult group. Thus, older people might undergo fewer changes in terms of transferring their body weight upon this foot during the loading response of the stance phase in compared to adult subjects, who showed earlier transferring of the body weight. They recorded higher contact and peak pressures under most of the plantar regions selected in the study compared to the older adults group.

It is imperative to analyse loading patterns under the foot during the mid-stance phase because it is essential to preserve standing balance upon one limb. This balance would unexpectedly be absent in this phase as the other foot started to rise from the ground, ready for swing phase, and for this reason it is necessary to underscore the gait study within the mid-stance phase during single limb support interval to ensure maintaining the balance ability and gait stabilisation required for older adults (Burnfield, 2010).

Older people recorded lower contact pressure values at both medial and lateral heel regions, suggesting that there was a tendency for older subjects to bear more weight on the mid-foot and forefoot regions during the mid-stance phase, compared with the results obtained from the adult group. That can be seen from higher contact pressures and peak pressures recorded not only at medial and lateral mid-foot regions but also in medial and lateral forefoot regions for older participants compared to that acquired from adult subjects. In addition, the results revealed lower contact pressure values in medial regions (mid-foot and forefoot) compared to that of lateral mid-foot and forefoot regions within the older adults' group during the mid-stance phase, indicating the trend to be on more weight bearing on their lateral side, similar to the findings of the study conducted by Hessert et al. (2005).

The higher contact pressure at the forefoot, including the metatarsal heads and the hallux area for older adults with relative to adults group of our own study, endorsed the results of the studies conducted by Franco et al. (2018) and Kwan et al. (2010). In contrast, the above results contradicted results found in research undertaken by Hessert et al. (2005) ; however, the measurement system differed from the one utilised in the current work. The high amount of pressure distributed on the hallux region for older adults demonstrated an association with the difficulties encountered by older adults, affecting their walking stability during loading phases of gait (Franco et al., 2018; Kwan et al., 2010; Menz et al., 2005). Furthermore, the higher contact pressures measured at the lesser-toes area for older adults relative to the adults group, except the region of second toe, would account for the most prevalent problem that face older people's lesser-toes: lesser toe deformities (Hannan et al., 2013; Mickle et al., 2011).

The higher peak pressure values, distributed in most of the plantar regions selected in the current study for older adults relative to those measured for adult subjects, are in line with the research conducted by McKay et al. (2017). Additionally, the higher peak pressures measured at the forefoot region for older adults compared to those in the adults group, reinforced by the results of research undertaken by Franco et al. (2018), could result from an alteration in terms of foot sensitivity in older people, particularly under the mid-foot and heel regions. Consequently, there was a trend to shift the plantar pressure from the insensitive heel area forward to the forefoot region (Machado et al., 2016) in order to preserve the balance ability over weight bearing tasks, especially during the mid-stance phase, in which one extremity has to be responsible to maintain the body balance necessary for older people during gait.

Regarding the push-down phase in which the contralateral extremity would experience the heel-strike of the stance phase of the human gait cycle, the body weight moves a head of the forefoot during this phase (Burnfield, 2010; Perry and Burnfield, 1993). The corresponding results did not record plantar pressure measurements at heel and mid-foot areas; however, a tiny amount has been appeared for adults group under the lateral mid-foot area. Additionally, the higher contact pressures measured at both medial and lateral forefoot regions during the push-down phase for older adults compared to adult subjects corresponded to the results of a number of previous studies (Bosch et al., 2009; Lane et al., 2014; Machado et al., 2016; Menz et al., 2013), leading to the development of forefoot pain (Keijsers et al., 2013; Lee et al., 2014), which can increase the risk of skin breakdown, injuries, and also the risk of falling (Chang et al., 2014; Menz et al., 2018; Mueller et al., 2003). The higher contact pressure distributed at the lateral forefoot area for older adults was amplified by decreasing the contact area relative to adult subjects. Consequently, more pressure distributed with less area might develop foot injuries under that specific area (Ko et al., 2012; Putti et al., 2007).

It is worth noting that the results showed a clear increase in contact pressure values registered in the medial forefoot area compared to the lateral forefoot site during the push-down with the older adults group participating in the study. The higher contact pressures located at the first, second, and third metatarsal heads compared to the fourth and fifth ones have demonstrated the above statement. In a study of the aging effect on the biomechanics of the plantar soft tissues, an increase was shown in the stiffness of the plantar soft tissues at the first and third metatarsal heads than the fifth metatarsal head for a number of people aged over seventy-one (Kwan et al., 2010). Increased stiffening means that the soft tissues would have less capability for pressure redistribution, leading to impairment of the cushioning properties of the soft tissues under the sites with high pressure such as the medial forefoot site (Gefen, 2003). This impairment can contribute to failure to achieve postural control during weight bearing tasks (Kwan et al., 2010), affecting the foot stability during the stance phase. As a result, elderly people may develop a number of foot complaints (Hsu et al., 2005). During this phase, older adults results recorded higher contact pressure values in the hallux area accompanied by less area of contact, indicating the development of foot injuries and deformities at this site (Ko et al., 2012; Putti et al., 2007).

The results of this investigation pointed to an increase in the peak pressure measures during the push-down phase, concentrated at the medial part of the forefoot region, recording higher peak pressures particularly on the first, second, and third metatarsal heads for older adults in comparison to adult participants, while the subjects were barefoot. The result was in line with the outcomes of the studies conducted previously (Chiu et al., 2013; Kernozek et al., 1995; Menz and Morris, 2006; Zammit et al., 2008). Although the medial forefoot had a slightly bigger area of contact for older adults relative to that of the adults group measured in the present study, this cannot compensate for the massive increase in peak pressure measures registered at that area during the push-down phase (Dowling et al., 2001). This increase can cause foot damage (Levangie et al., 2000); therefore, older adults appear to be at greater risk of developing stress fractures at their medial forefoot area due to increased dynamic peak pressures during weight bearing tasks (Dowling et al., 2001; Levangie and Norkin, 2000). Based on these findings, forefoot peak pressure can be considered to be a major concern for older adults whereby a number of health implications can be related with an increase in its value.

Additionally, the five metatarsal heads had recorded higher peak pressure amounts along the whole mid-stance and push-down phases, indicating that the forefoot region, in particular the metatarsal heads, can be considered as the most vulnerable part of the plantar surface while older people were performing barefoot gait trials in relation to adults group. The research outcomes of the studies conducted by McKay et al. (2017) and Franco et al. (2018) were in line with our current work.

Importantly, the poorer distribution of the plantar pressure under the metatarsal heads for older adults during the push-down phase can be attributed to the pressure redistribution behaviour of the contralateral foot, which exhibited a reduction in pressure values under the heel area during the initial contact phase with close contact area values between the two groups participating in the present study. A greater contact area for gait cycle initiation can allow for better plantar pressure distribution (Sneyers et al., 1995). As a consequence, the abnormal behaviour of plantar patterns during the heel-strike for one extremity can lead to poorer distribution for the contralateral extremity for older adults, which would be experienced the push-down phase (Burnfield, 2010; Perry and Burnfield, 1993). Furthermore, the higher peak pressure under the metatarsal heads sustained by older adults in the current study can be related to the foot landing way adapted as a mechanism to maintain the body balance necessary to efficiently terminate the stance phase of the gait cycle (Franco et al., 2018; Kwan et al., 2010; Machado et al., 2016).

Noticeably, the increase in contact pressure values for older adults under barefoot condition were followed by an increase in peak pressure readings, mainly under the hallux and lesser-toes, except the region of toe 2 relative to the results of the adults group. A number of previous studies, which have been mentioned in the discussion section provided in chapter 3, reported that increasing peak pressure magnitudes beneath these areas could increase the risk of foot injuries and the development of foot deformities with advancing age.

Throughout the toe-off phase, the results kept exhibiting higher contact pressure values for older adults under the metatarsal heads than that measured for adults group. It seems that older adults made contact with the ground with their metatarsal heads during the toe-off phase, possibly to provide the proper and safe termination of the stance phase of the gait cycle. Altered pressure patterns at the metatarsal heads for older adults measured in the present study can be attributed to the foot landing way adopted as a mechanism to maintain the balance essential to eventually terminate the stance phase of the gait cycle (Franco et al., 2018; Kwan et al., 2010; Machado et al., 2016). Furthermore, higher contact pressure values were recorded under the big toe and lesser-toes regions for older adults compared to the results of the adults group. However, the toe 2 site had less value for the older adults group.

Additionally, the results revealed a noticeable difference in peak plantar readings, recording higher peak plantar pressure measurements at the forefoot area, specifically under the medial part of this region. These higher peak plantar pressure measurements can be seen from the higher peak pressure values located beneath the first and second metatarsal heads for older adults relative to the adults group. Moreover, the hallux region for older adults during the toe-off phase had higher peak pressure values compared to those measured for adult subjects. The pressure characteristics at the hallux region during the toe-off phase for older people in our own study are likely to preserve the balance ability over weight bearing tasks for safe termination of the stance phase of the gait cycle.

The outcomes of the present study highlighted higher peak pressures in the older adults group. This can be explained by the ankle-foot mechanical properties associated with age-related changes and by the changes in the plantar soft tissues (McKay et al., 2017). Therefore, excessive peak pressures located at the forefoot region, including the hallux area in the older adults group during loading phases of gait can result in foot injuries and the development of ulcers. This would account for the common conditions sustained by older adults at their forefoot site, including the metatarsal bones region, affecting their stability during gait (Kwan et al., 2010; Wang et al., 1999).

It is also important to mention that the lesser-toes region had higher peak pressure readings in relation to those obtained from adult subjects of our own research during the toe-off phase, except the toe 2 region, which showed lower values for older adults. These results were consistent with the results obtained during the mid-stance and push-down phases. Being on higher peak pressures for prolonged period beneath the hallux and lesser-toes regions for three consecutive phases within the stance phase of the gait cycle for older adult group, with less area of contact recorded, in particular at the hallux area during push-down and toe-off phases, might cause the development of foot or gait injuries (Ko et al., 2012; Putti et al., 2007), and accordingly these regions would be at risk of developing toe deformities common in older adults (Hannan et al., 2013; Mickle et al., 2011), which might hinder maintaining the body balance and increase the risk of falling sustained with advancing age during loading phases of gait (Mickle et al., 2011).

5.6 Case study for un-normalised and normalised plantar pressure distribution comparison between older adults and adults while single limb support interval

The study aimed to investigate whether the variance of subjects' weight and contact time exerted in the stance phase, in which the foot is in contact with the ground during the entire period of this phase has an influence on changing the difference of plantar pressure and peak plantar pressure values between the two cohorts compared with un-normalised plantar pressures and peak plantar pressures specifically during the mid-stance phase when one limb has to be responsible for supporting human body weight.

Eighteen trials were collected from six participants who were recruited in this study, three older adults aged 65-75 years (mean age 68.7 ± 5.5 years, weight 88.3 ± 16.7 kg, and height 177.7 ± 9.1 cm), and three adults aged 33-38 years (mean age 36 ± 2.6 years, weight 79 ± 4.6 kg, and height 173.7 ± 6 cm). The mean contact time required for accomplishing the whole stance phase for both older adults and adults was (1.06 ± 0.29, 0.8 ± 0.11 sec), respectively. The subjects were requested to perform the two-step gait protocol, in which plantar parameters were recorded when second step contact was made with a Tekscan floor pressure mat (Bus and de Lange, 2005; Chevalier et al., 2010) to measure their plantar pressure parameters. The research adopted MatScan® (Tekscan, Boston, MA) plantar-pressure mapping systems to capture plantar parameters, such as contact pressure, and peak plantar pressure.

In order to discuss the un-normalised plantar pressure data with both weight-normalised and time-normalised data for the comparison between older adults and adult subjects, it is imperative to analyse loading patterns under the foot during the mid-stance phase because it is essential to preserving standing balance upon one limb. This balance would unexpectedly be absent in this phase as the other foot started to raise from the ground, ready for the swing phase, and that is why it is intrinsic to underscore the gait study in mid-stance phase to assure keeping balance ability and gait stabilisation desired for older adults (Burnfield, 2010; Fuchioka et al., 2015; Riva et al., 2013).

Figures 5.23, and 5.24 point out the comparison values between older adults and adults of contact pressure, and peak contact pressure, respectively. Figure 5.25 and Figure 5.26 depict the values of contact pressure and peak plantar pressure comparison between older adults and adults, taking into account the subjects' weight that hypothetically might affect the amount of pressure and peak pressure distributed in fifteen plantar regions. The contact pressure and peak contact pressure values normalised to each subject's weight individually appeared relative changes in differences of these parameters between the two cohorts. However, these values showed no differences with respect to the original data in terms of higher pressures and peak pressures in most of selected plantar regions adopted in this research.

The trend toward a longer contact time from older adults on the pressure mat has also been explored in this study to reveal the contribution of the required time to complete the entire stance phase, by each subject participating in either group, on pressures and peak pressures distributed in chosen plantar regions shown in Figure 5.27 and Figure 5.28.

In the context of analysing plantar parameters with taking into consideration, normalising to the time required to finish the stance phase of the human gait cycle by each participant, the pressures and peak pressures still recorded higher values in older adults compared to the results of the adults group. However, there were some variances in differences of the plantar measurements between the two groups, relative to the original data. Thus significance was that, even when the subjects' weight and the total time needed to finish the stance phase of gait cycle were considered by each subject in conjunction with computing pressures and peak pressures during ambulation, particularly in the mid-stance phase, the results revealed higher values in most of the plantar regions for the older adults group when compared to the adults group.

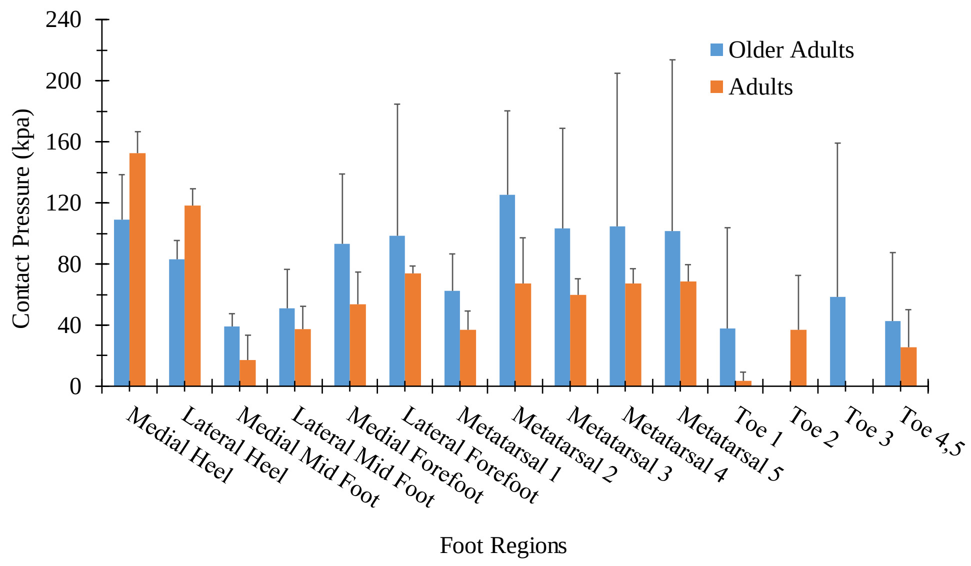

Figure 5.23: Mean and standard deviation of un-normalised contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

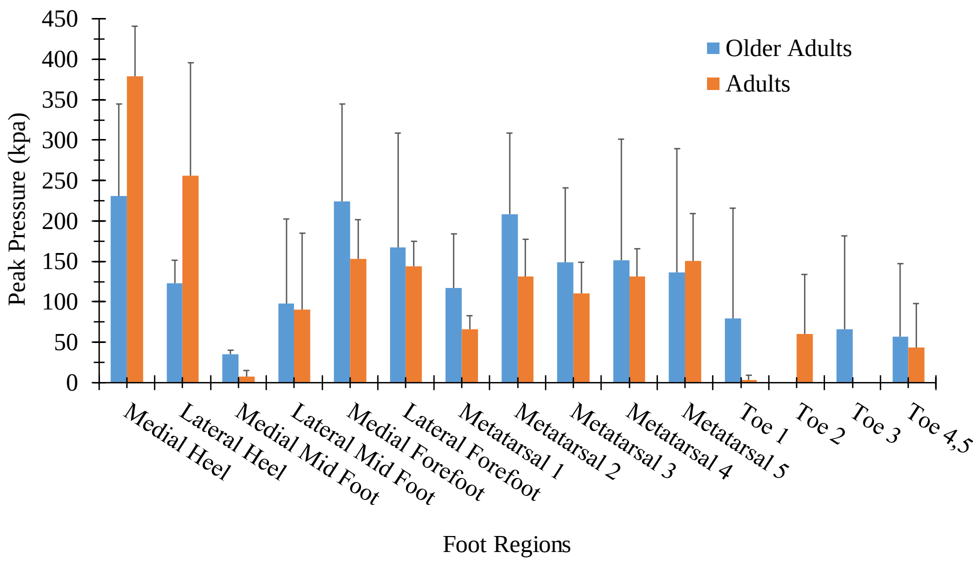

Figure 5.24: Mean and standard deviation of un-normalised peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

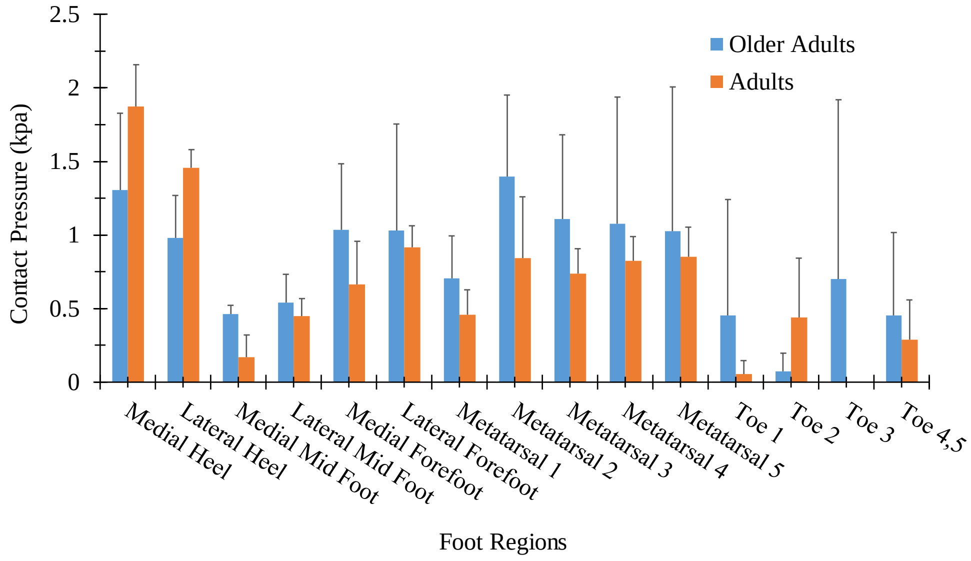

Figure 5.25: Mean and standard deviation of weight-normalised contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

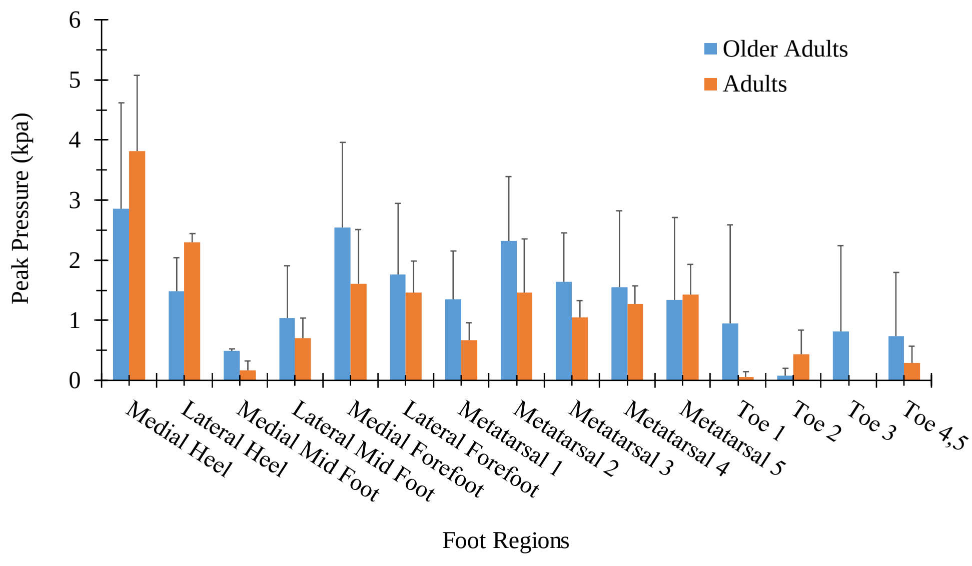

Figure 5.26: Mean and standard deviation of weight-normalised peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

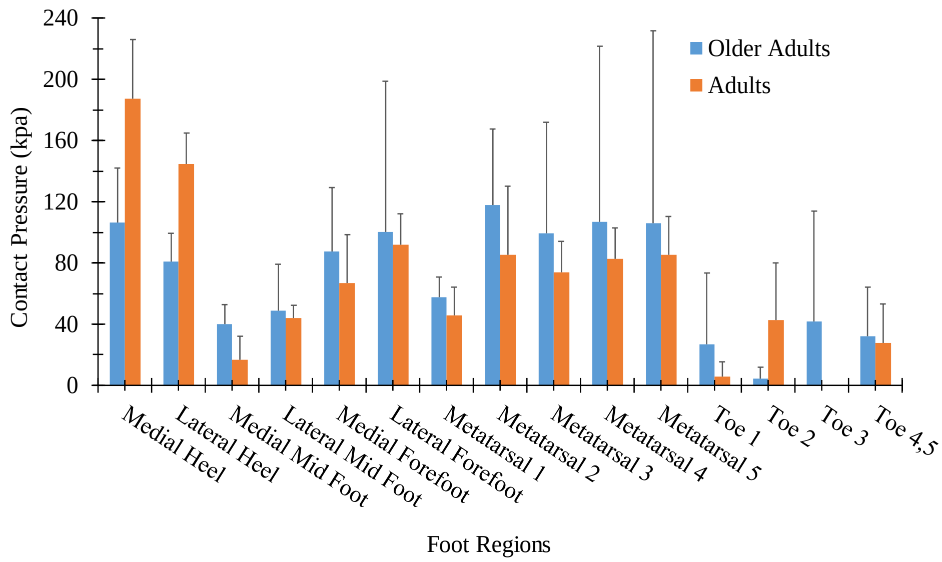

Figure 5.27: Mean and standard deviation of time-normalised contact pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

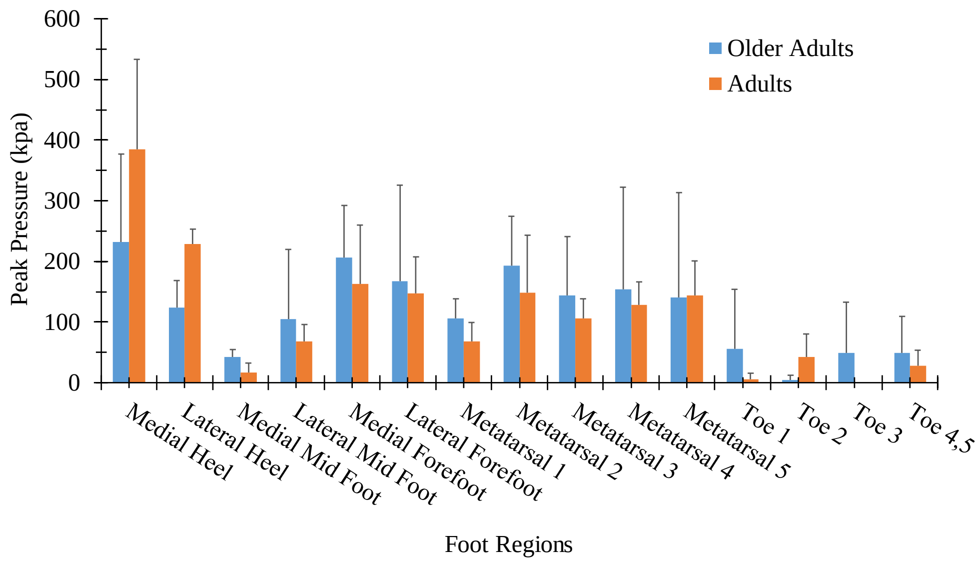

Figure 5.28: Mean and standard deviation of time-normalised peak plantar pressure values in (kpa) for comparison between older adult and adult groups of three walking trials for each subject in 15 selected plantar regions during mid-stance phase.

5.7 Conclusion

The research was carried out firstly to study the influence of contact pressures and peak plantar pressures distributed in fifteen plantar regions during loading phases of gait on foot complaints encountered with advancing age via a comparison adopted between older and adult subjects. Furthermore, the research was conducted to detect whether involving subjects' weight and the required time to complete the gait cycle by each participant had an impact on changing the differences of contact pressure and peak pressure between the two groups participating in the study. This was performed in particular during single limb support tasks, at the mid-stance phase interval, because of the need to examine the changes in loading patterns of the foot with advancing age when one limb has to be responsible for supporting human body weight.

Higher values of contact pressure and peak pressure were located underneath the forefoot region, specifically under the metatarsal heads and the hallux areas for older adults compared to those obtained from adults. These higher values were detected in particular during the mid-stance, push-down, and toe-off phases. This means that the mentioned regions would be the most vulnerable ones among the whole plantar surface. In addition, weight and time normalised data analysis performed at mid-stance phase revealed high similarities to the one conducted for the un-normalised data. The normalised comparisons emphasised that higher contact pressure and peak pressure values were found in most of selected plantar regions for older adults compared to those obtained from adults.

The plantar pressure measurements captured during five phases included in the stance phase of the gait cycle were essential in terms of enhancing the visualisation of pressures and peak pressures distributed along the whole plantar surface of the foot, thus providing insights into plantar patterns variations due to increasing human age. The study could enhance the understanding of reasons beyond body balance problems and instability of walking suffered by older adults, and accordingly discover whether the balance deficiencies and foot complaints would be related to certain phases, included in the stance phase of the gait cycle specifically. The next chapter addresses the techniques developed based on 3D gait phase image and plantar pressure pedobarographic image for the comparison between older adults and adults.

CHAPTER SIX

ADVANCED TECHNIQUES OF 3D GAIT PHASE IMAGE AND PLANTAR PRESSURE COMPARISON BETWEEN OLDER ADULTS AND ADULTS

6.1 Introduction

Due to age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during gait, could result in serious injuries. The risk of falls sustained by older people can increase because of stability and balance impairment, which in turn may impair the foot function during normal gait. It is well known by previous studies that most foot problems, including falls encountered by older adults, occur during gait. Furthermore, the scientific and clinical evaluation of foot and gait pathologies can be obtained by performing plantar pressure distribution measurements. Therefore, this investigation involved innovative techniques to perform the correlation between human 3D gait phase images and the corresponding plantar pressure images. Thus, the research was carried out to examine foot rotation and loading based on integrating human lower limb movement with its corresponding plantar pressure data, which was the ultimate goal of the present study. The 3D models of the human lower limb and foot were obtained using photogrammetric techniques, whereas a set of plantar pressure data was acquired through floor-based pressure mat systems. The correlation of analysed gait data and plantar pressure measurements has been achieved by combining them, thus yielding new data. The created data was eventually adopted to identify the discrepancies in the gait characteristics between older adults and adults. Participants were recruited in the study to perform typical barefoot walking. The research developed a high-accuracy correlation technique based on the 3D lower limb and foot movements and the plantar pressure measurements. The correlated data permitted full comparison and evaluation of the gait trial based on barefoot walking of older adults and adults participating in the study.

6.2 Background

The human body part that connects the human body with the ground is the foot, which is integral to human gait (Rodgers, 1995). Human gait can be utilised for assessing the quality of life, the health condition, and the physical functioning of older people (Cesari et al., 2005; Hollman et al., 2011). Due to age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during ambulation often result in injuries (Day, 2003; Lord et al., 2007; Menant et al., 2008; Mickle et al., 2010; 2011; Rubenstein, 2006). The risk of falls sustained by older people can increase as a consequence of stability and balance impairment caused by any factor that may impair foot function during normal gait (Mickle et al., 2010). Foot pain is recognised as one foot-related factor that affects older adults in terms of gait, balance, and normal foot function (Menz et al., 2001). A number of recent studies established that there is a clear association between foot pain and elevated plantar pressures for older people during gait. Forty subjects with a pes cavus foot type were compared with thirty subjects with normal foot type. It was found that there is a significant correlation between pressure-time integrals and foot pain, and the subjects who suffered from foot pain had considerably higher values of pressure-time integrals for the entire foot than those who had no pain in their foot (Burns et al., 2005). In a sample of three hundred and twelve community-dwelling older men and women aged over 60 years, the effects of toe deformities on the gait, balance, and plantar pressures were studied. Spatiotemporal parameters of the gait were measured using an Emed-AT4 pressure plate. The results in relation to older people with lesser toe deformities and hallux valgus showed alterations in patterns of forefoot plantar pressure and, in turn, these changes impaired gait and balance for selected subjects (Mickle et al., 2011).

It is essential to understand the dynamic behaviour of the normal functional foot in order to compare it with the symptomatic foot (Rodgers, 1995). The anatomical foot deformities for those patients with an symptomatic foot can be identified by measuring their plantar pressure distribution during walking (Hessert et al., 2005a; Rodgers, 1995). For instance, the appearance of ulceration and the risk of tissue injury can be linked with elevated plantar pressures during walking (Burnfield et al., 2004; Frykberg et al., 1998). In a sample of fourteen diabetic neuropathic patients, the subjects made contact with the pressure platform using various step protocols to obtain dynamic barefoot plantar pressure measurements. A number of plantar pressure parameters such as pressure-time integral, peak pressure, and contact time were measured and intraclass correlation coefficients were calculated for assessment of the reliability of the results (Bus et al., 2005). In general, the structure of the human foot changes with advancing age (Burnfield et al., 2004; Hessert et al., 2005a; Rodgers, 1995). In order to maintain independence and to diminish the risk of falling for older people, it is vital for them to maintain the safety and efficiency of their walking ability (Callisaya et al., 2010; Mickle et al., 2011).

Foot pressure distribution was measured for nine young and six elderly subjects wearing shoe insoles at normal walking speed. Mean and maximum force and pressure values were measured in nine anatomical masks created in the plantar surface. It was found that weight bearing in elderly subjects on the lateral side of the foot had an effect on their walking stability (Hessert et al., 2005a). Twenty older subjects were involved in the study of plantar pressure variables with different walking speeds and footwear conditions in eight foot regions. The results revealed that subjects had higher pressures in some selected foot regions under barefoot walking conditions and faster walking speed (Burnfield et al., 2004). In a study of a number of older people, aged 62-96 years using a floor-mounted resistive sensor mat system, plantar pressures and forces were measured. The aim of that research was to evaluate the relationships between a number of clinical tests of the foot and ankle with measured force and pressure values under the foot, which might explore clinical interventions for plantar pressure pattern modifications (Menz et al., 2006).

Despite the growing use of plantar pressure measurements for research purposes, there has been little integration of these data with lower limb and foot movement data, particularly for older people. Therefore, the aim of this study was to integrate the human lower limb movement with its corresponding plantar pressure data to examine foot rotation and loading for older people. In doing so, this can provide insights into studying the changes of the human gait movement and plantar pressure parameters with advancing age by observing the correlation between both obtained data for selected subjects of both cohorts: older adult and adult. The correlation technique based on photogrammetric measurements and the centre of pressure trajectories developed in the current work will be presented in this chapter.

6.3 Research methodology

6.3.1 Participants

The results were collected from participants (older adults and adults) who were recruited in the study while performing typical barefoot walking. The participants consisted of three older adults (age: 72, 65, and 66 years old; weight: 83, 107, and 75 kg; and height: 188, 174, and 171 cm), and three adults (age: 38, 33, and 39 years old; weight: 78, 84, and 75 kg; and height: 173, 168, and 180 cm). Human subjects participated in this research under an approved ethical application (H18REA160) obtained from the University Ethics Committee.

6.3.2 Research equipment and theoretical tools

The research adopted a MatScan® (Tekscan, Boston, MA) plantar-pressure mapping system to capture plantar parameters, such as contact area, contact pressure, and peak plantar pressure. The pressure mat systems contained resistive load cells. These sensors converted the individual's load into an electronic signal. A USB interface transferred the electronic signals formed by the pressure mat system to the computer device to be manipulated by specific software (Tekscan) necessary to measure and analyse plantar pressure parameters. For clarification, the plantar pressure data was recorded through floor-based pressure mat systems when each subject started walking on the floor-mat. The subject first touched the pressure mat with the heel area which means the load was applied to the sensors. Then, these sensors or resistive load cells of the pressure mat converted the subject's load into an electronic signal by changing its resistance which in turn led to a change in output voltage. The electronic signals were transferred via a USB interface to the computer device.

Five video cameras (Panasonic Lumix DMC-FZ300 Digital Camera) were utilised in the close-up photogrammetric multi stereo-video recording (Al-Baghdadi et al., 2013). The photogrammetric system was accompanied by two control boards located at both sides of the walk way which are necessary to obtain the required measurements. The five video cameras had to be calibrated. The calibration process and lens parameters calculation to individual video cameras was implemented using the self-calibration technique. Video frame extraction of the obtained video clips was conducted for each captured video clip. Two programs were used in the video frame extraction, namely: (1) Free make Video Converter for video format converting; and (2) Virtual-Dub for video clip to image conversion.

The exposed area of the subject's lower limb and foot was marked with a fine-tipped black permanent marker at desired anthropometric landmarks to ensure reliable data. In addition, a calibrated scale bar consisting of a number of signalised target points was taped on the subject's leg. This scale bar was used as a device for measuring the system accuracy when the subjects conducted the imaging sessions. For each subject, video clips were captured via the photogrammetric systems. The calculation of the measurements of human lower limb movement was obtained for both older adults and adults to the desired targets located on the subject's lower limb and foot. The 3D measurements were computed by using off-the-shelf camera calibration software Australis®.

The subjects were asked to perform a two-step gait protocol, in which plantar parameters were recorded when second step contact was made with a Tekscan floor pressure mat (Bus and de Lange, 2005; Chevalier et al., 2010; Meyers-Rice et al., 1994). A standard gait procedure was carried out by participants represented by the position of standing at the commencement, followed by proceeding forward to step on a pressure mat, and repeating the test three times for measurement purposes. Few minutes were given to each participant before the commencement of the gait trials to practise the test, thereby positioning the subject's foot on the floor-mat and avoiding alteration to the required step characteristics of the research.

A red flash LED attached to one of the two control boards was crucial for system synchronisation between the lower limb and foot model data and the plantar pressure data. Combining the gait data with the plantar pressure data to analyse the differences between the two cohorts was the ultimate goal of the present study. Generally, the gait tests investigation involved combining 3D lower limb movement measurements with plantar pressure data for both older adults and adult subjects as a control data. The outcome of these measurements was adopted to correlate the movements of human lower limb with the corresponding plantar data. The two main techniques adopted in the study will be explained in the following section.

6.3.3 Gait study

6.3.3.1 Performing the gait trials

Menz and Morris (2006) recorded plantar pressure measurements for defining clinical determinants of foot and ankle characteristics that could explain the difference in pressure patterns during walking in older people. The study adopted the two-step gait protocol for obtaining plantar pressure measurements under seven regions of the foot. Using the two-step gait protocol was found to be adequate for ensuring reliable plantar pressure measurements with only three trials of data collection. However, a number of data collection techniques relevant to performing the gait trial were presented in the literature review chapter. Furthermore, Bus and de Lange (2005) presented a barefoot plantar pressure measurement for the evaluation of the ulceration risk for patients suffering from diabetes and neuropathy. The aim of the research was to make a comparison between three common step-protocols (one-step, two-step and three step) adopted for plantar assessment of 14 diabetic neuropathic patients. From the findings of the research, it was apparent that to obtain reliable pressure data in terms of the minimal number of repeated trials, the two-step protocol was recommended for assessment of these patients (Bus and de Lange, 2005; McPoil et al., 1999; Perttunen, 2002).Therefore, in the current research, the individuals were asked to perform a two-step protocol with normal gait across the pressure mat to ensure reliable plantar pressure measurements with a limited number of trials.

In the gait test, before the trial, the subjects were given sufficient time to practise the procedure in which plantar pressures were obtained on the second step when the foot landed on the pressure mat, as part of the two-step gait protocol. During that time, the subjects were asked to repeat the trial of the gait on the walkway, including the pressure mat, between three to five times to ensure having an identical plantar pressure pattern for each trial to acquire reliable pressure data. In the meanwhile, the video clips captured the whole lower limb and foot via a photogrammetric system involved in the current study. By synchronising the specified frames from the captured video clips with the plantar pressure data recorded through the subject’s gait, it was possible to obtain the integration of the planter pressure data with the individual’s lower limb and foot gait data at a required particular time. The means of the synchronisation adopted in the current research will be discussed and explained with details in the next sections.

6.3.3.2 Plantar pressure parameters measurement for gait study

In the context of the plantar pressure distribution measurements, a number of studies have employed the Tekscan pressure systems for the measurements of plantar pressure patterns for subjects, whether healthy or with different pathologies during walking (Chevalier et al., 2010; Chong et al., 2014; Menz and Morris, 2006). Research showed that these systems are reliable and accurate for plantar forces and pressures for barefoot level conditions (Brenton-Rule et al., 2012; Giacomozzi, 2010; Hafer et al., 2013; Zammit et al., 2010), making these systems appropriate for both research and clinical settings (Brenton-Rule et al., 2012; Hafer et al., 2013).

The research adopted a MatScan® (Tekscan, Boston, MA) for platform based plantar pressure measurement. Basically, the systems include a floor mat (432 * 368 mm) of 5 mm thick, which consists of 2288 individual locations of pressure sensing called sensing elements with 1.4 sensors/ cm^2 as their spatial resolution. The system had to be calibrated prior to the gait tests session conducted for each subject. The calibration process was implemented using the body weight for each tested subject according to manufacturer's guidelines.

As mentioned earlier, for the data collection process, the subjects were instructed to perform the two-step gait initiation protocol (Bryant et al., 1999; Bus and de Lange, 2005; McPoil et al., 1999; Meyers-Rice et al., 1994; van der Leeden et al., 2004) to capture plantar parameters, such as contact area, contact pressure, peak pressure, and COP trajectory.

The gait test procedure commenced with the position of standard human standing, followed by proceeding forward and stepping with the foot on a TekScan floor pressure mat where the second step was recorded. The test was repeated three times for each participant so a reliable plantar pressure data could be obtained. Three walking trials were found to be sufficient for achieving the required reliability of the plantar pressure data (Bryant et al., 1999; Giacomozzi, 2010; Hafer et al., 2013; Menz and Morris, 2006; van der Leeden et al., 2004).

In order to ensure that the correct foot was placed on the floor-mat without alteration of the gait, the participants were given few minutes to practise the procedure before starting the tests session. For regional plantar pressure measurement analysis, the study used the FSCAN Research, version 6.7 software to construct individual masks under a number of plantar regions. The masks were analysed to determine and study the foot loading pattern variations for the entire stance phase of the gait cycle for older adults and adults under barefoot walking conditions via floor-based pressure mat systems shown in Figure 6.1.

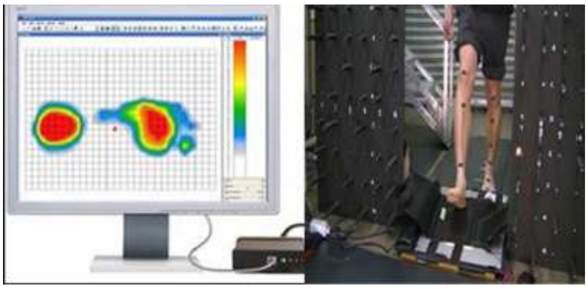

Figure 6.1: Walking on the pressure mat between the two control boards by an older adult on the (right), plantar pedobarographic image captured by plantar pressure measurement system on the (left).

In the study, a number of plantar pressure parameters, namely the contact area, contact pressure, peak pressure, pressure-time integral along with the COP trajectories, have been extracted for the two groups participating: older adults and adults during the stance phase of the gait cycle, obtained by analysing their associated plantar pressure images. These videos were captured while the subjects were walking barefoot on the pressure mat using Tekscan measurement systems in order to distinguish the discrepancies of the gait characteristics between older adults and adults during the loading phase of gait.

6.3.4 3D photogrammetric computation techniques

6.3.4.1 Calibration of the research video cameras

In order to attain high accuracy measurements in close range photogrammetric work, it is essential to perform the process of camera calibration. Therefore, all video cameras had to be calibrated in the current research. This calibration was performed by finding significant parameters, including the interior orientation parameters (xo, yo, f), radial distortion parameters (K1, K2, K3), and the lens alignment parameters (P1, P2, P3) (Remondino et al., 2006; Udin et al., 2011). A calibration technique which does not require a set of known object-space coordinates of the signalised targets photographed is required (Chong et al., 2009); furthermore, it is well known that to achieve accurate and reliable 3D metric information from images captured by video cameras, it is essential to use an accurate camera calibration approach such as self-calibration technique. According to Fraser et al. (2006), self-calibration is the technique in which the values of lens parameters at various zoom values are determined by means of a set of convergent images of a photogrammetric test-field. Each convergent image should cover the test-field entirely.

Chong (2012) adopted the technique of self-calibration to calibrate the research camcorders for determining the lens parameters values. The research results revealed that these camcorders are able to provide an accurate 3D measurement of about one-tenth of a millimetre at an object distance of 800 to 1200 mm. The calibration of three digital cameras based on the method of self-calibration bundle adjustment produced optimal results in terms of measurement accuracy and precision (Udin and Ahmad, 2011). The authors stated that the self-calibration bundle adjustment is the most widely used and popular method due to its suitability for calibrating digital cameras.

Therefore, the self-calibration technique was used in the current research to calibrate the selected cameras individually. Regarding the research gait test, the position of the camera mount and the calibration board was adjusted. The principal distance (PD) was set at a wide-angle setting as this allows an optimal coverage of the scene. In order to ensure unchanged PD for the whole test, the camera zoom device was fixed by tape. The length and width of the test-field was 800 and 600 mm respectively, accompanied by targets of various heights from 0 to 150 mm. A high-precision Invar bar was placed in the middle of the signalised target board (Chong et al., 2009), as appears in Figure 6.2.

The self-calibration technique is accomplished through a number of steps: (1) three sets of four convergent video clips (four up right, four rotated 90° to the left, and four rotated 90° to the right) of the test-field are captured to determine the values of the lens parameters as discussed by Fraser and Al-Ajlouni (2006); (2) individual frames are extracted from the video clips; and (3) the extracted frames are processed via the bundle adjustment process which is carried out using the Australis bundle adjustment software. For clarification, the bundle adjustment is the process in which x, y, and z coordinates of the object point of interest and the sensor calibration are obtained. A set of 12 convergent images for each selected digital video camera was obtained, as shown in Figure 6.3. These convergent images were digitised and processed using Australis, a bundle adjustment photogrammetric software to compute the parameter values for all used video cameras. These parameters were used then to process the frames extracted from the individual's gait video clips, thereby obtaining the required 3D measurements of the desired anthropometric marks on individual's lower limb and foot (Chong, 2012; Chong et al., 2009).

Figure 6.2: Camera calibration target board "test-field".

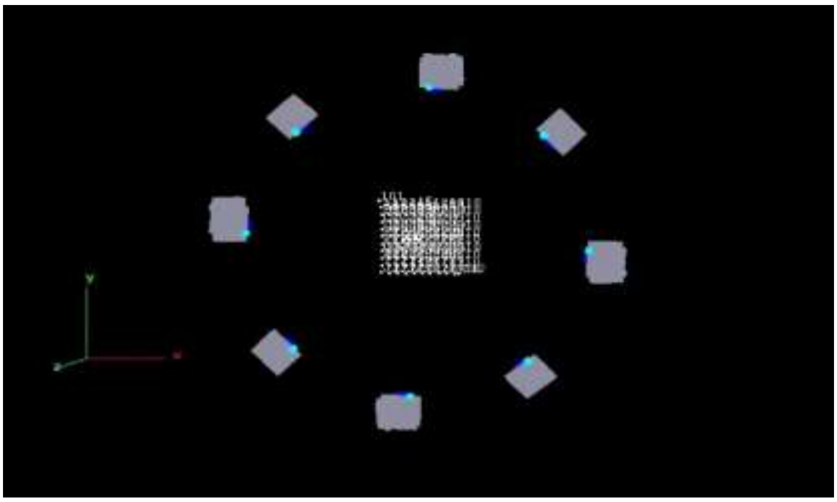

Figure 6.3: Image configuration for 3D camera calibration board with multi-camera positions.

6.3.4.2 Acquiring 3D spatial coordinate measurements

Due to the complicated human body shape, especially in the craniofacial area, the hands and the feet, human body measurement and mapping require multi-camera imaging systems (Chong, 2011). Therefore, photogrammetric computation techniques have been used in this research to accurately obtain the required targets on the individual's lower limb and foot. The photogrammetric computation technique required in the current research comprised a multi-video camera system accompanied with two control boards. An imaging session of this research consisted of taking convergent video clips while the cameras were aimed at the centre of the individual's walkway. Then, the video frames of an individual's lower limb and foot were extracted as the same time as movement for photogrammetric computation processing technique occurred. In order to prepare the bundle adjustment in Australis, a number of steps were required: (1) the PD and the lens parameters (Xo, Yo, K1 and K2) values obtained from a self-calibration were used in the template of the camera parameter; (2) the PD was set to free; (3) the lens parameters were set to fix; and (4) a constraint network bundle adjustment was carried out using the known coordinates of the control points existed in the control board. Being able to complete the implementation of the bundle adjustment process, the 3D coordinate measurements of a set of desired anthropometric marks created by researcher on individual's lower limb and foot were precisely obtained, Figure 6.4.

Figure 6.4: Anthropometric marks on individual's lower limb and foot.

In the context of the videos captured for the human lower limb and foot using photogrammetric systems, five video cameras were utilised in this research to guarantee the covering of the whole object and allow for accurate computation of the required 3D measurements. The individual's lower limb and foot locomotion during gait were captured through video clips obtained using a multi-video camera system. The test involved capturing an individual's lower limb and foot movement during gait while the subjects were walking between the two control boards, Figure 6.5.

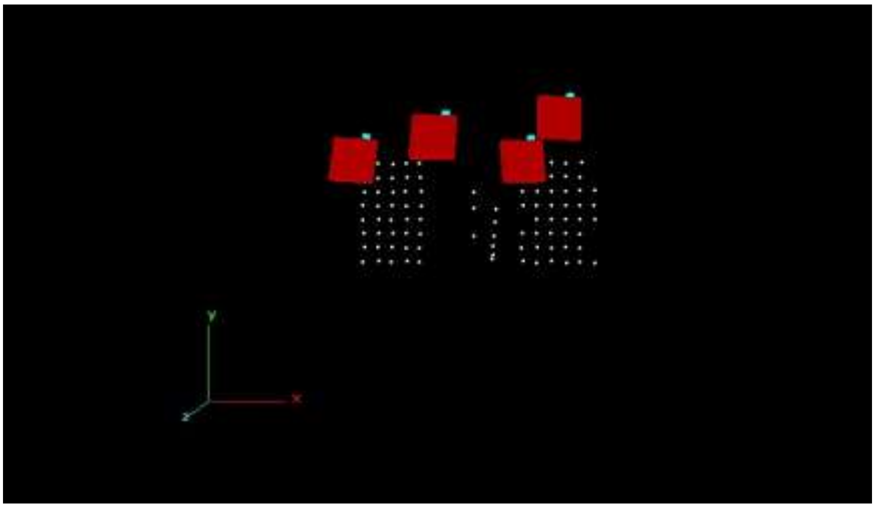

Figure 6.5: 3D viewing of imaging session as it appeared in Australis software.

In terms of visualising geometrical changes by using a photogrammetric system, a photogrammetric technique developed by Chong et al. (2009) was adopted to measure the changes in spine length and to examine the angular changes in spine shape. For instance, the changes in the shape of the spine angles were derived from the calculation of 3D coordinates of anthropometric landmarks located in subject's spine. The results proved that the measurement of these landmarks associated with the angles between spinal segments were accurately obtained. Therefore, it was important to adopt a photogrammetric technique in the current research, thus yielding high-accuracy measurements of the landmark coordinates necessary to study the dynamic changes of an individual's lower limb and foot, Figure 6.6. After detecting an accurate and reliable anthropometric landmark measurement, the desired measurement of lower limb and foot of subject movement during a gait cycle was achieved to eventually obtain the differences in these measurements between the two cohorts selected in the study: the older adults and adult subjects.

Figure 6.6: 3D viewing of anthropometric landmarks on the subject's lower limb and foot with the two control boards as it appeared in Australis software.

6.3.5 Integrating 3D lower limb and foot data with plantar pressure data

It was crucial to include a synchronisation electronic device in the current research in order to establish the correlation between the 3D lower limb and foot measurements captured by multi video camera systems and the measurements recorded by the plantar pressure systems. A red-flash LED attached to one of the two control boards was adopted as a synchronisation mean which turned on at the same time as strike the floor-mat by the subject's heel during the heel-strike phase, Figure 6.7. It was necessary to ensure that the specific images, which represented the loading phases of gait in the F-scan system were selected according to the standard level of accuracy. Therefore, the video recordings captured of participants during walking detected the gait for each subject using five video cameras prepared beforehand. The stance phase (from heel-strike through mid-stance to toe-off phases) for each participant was monitored to ascertain the images associated with the phases to be investigated. For instance, the mid-stance phase predominantly occurred from about 12% and continued until 31% of the gait cycle, which was in line with the studies conducted by Burnfield (2010). The time was counted from the starting point at heel-down until the required moment relevant to each phase. Doing a matching calculation to compare this time with the corresponding time in the Tekscan system, the images that represented the heel-strike, mid-stance, and toe-off phases had been precisely achieved. The correlation of a number of measurements was attained when the computed lower limb and foot measurements were calculated using a set of extracted video frames at the same time as turning on the LED with the frames recorded from the plantar pressure systems.

It was important in this research to gather the 3D lower limb and foot data while locomotion obtained by photogrammetric systems and the plantar pressure data acquired by floor-based pressure mat systems. The data enabled identification of the differences of the gait characteristics, particularly during loading phases of gait, between older adults and adults. Therefore, the aim of the research required in the current chapter could ultimately be achieved. This work will be demonstrated in detail in the results, analysis, and discussion section. Figures 6.8, 6.9, and 6.10 show the images of the photogrammetric systems adopted in the current work, displaying the human lower limb and foot movements while the older adult was performing normal walking on the pressure mat. Simultaneously, images are shown of the plantar pressure measurement systems during the three main phases of the gait, heel-strike, mid-stance, and the toe-off, respectively.

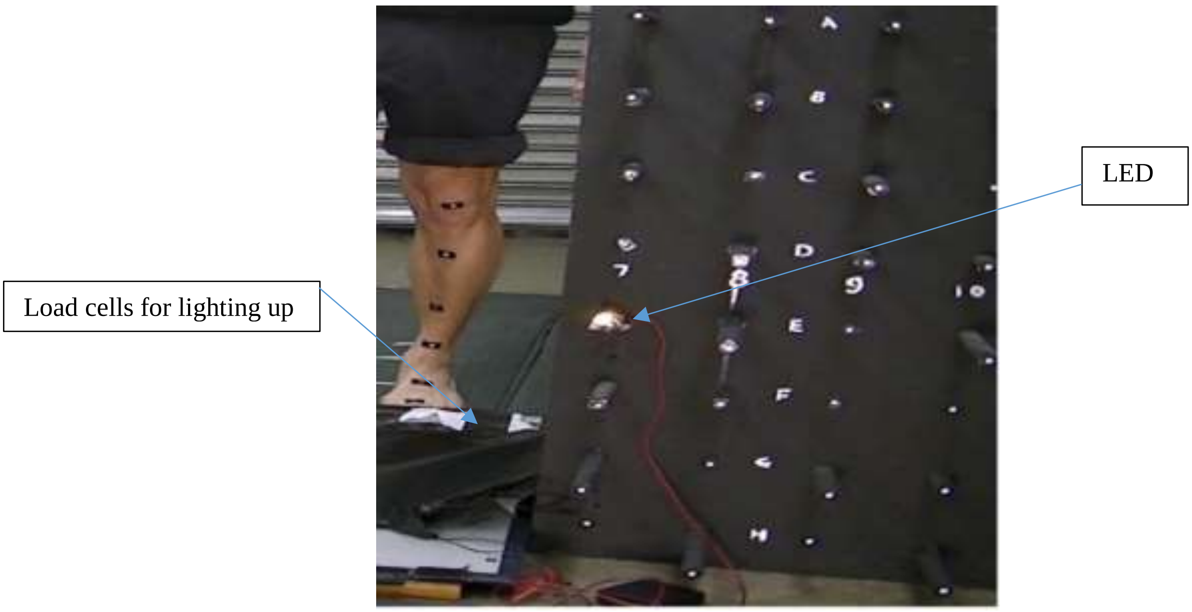

Figure 6.7: Synchronisation techniques adopted in the research.

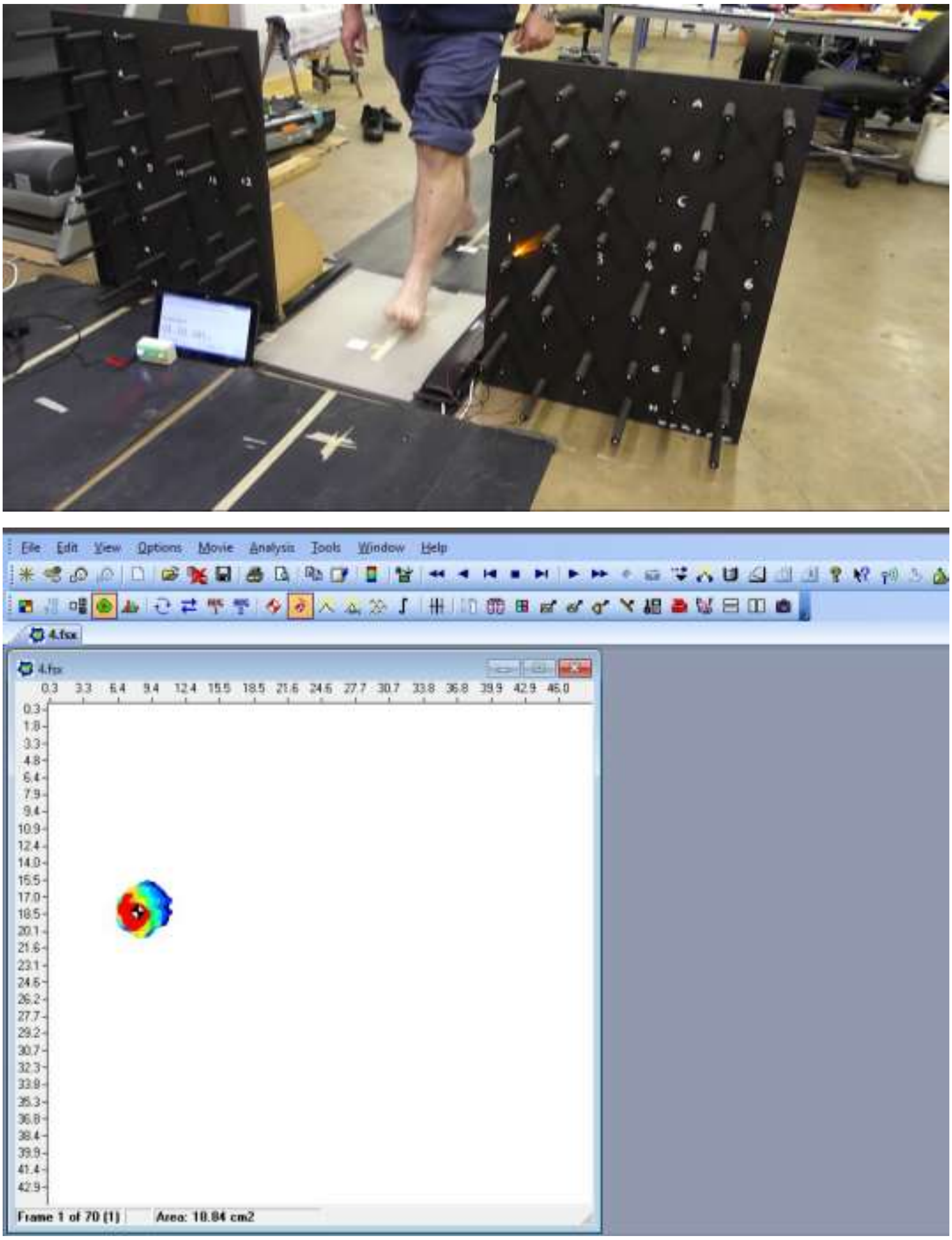

Figure 6.8: Photogrammetric system with the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at heel-strike phase.

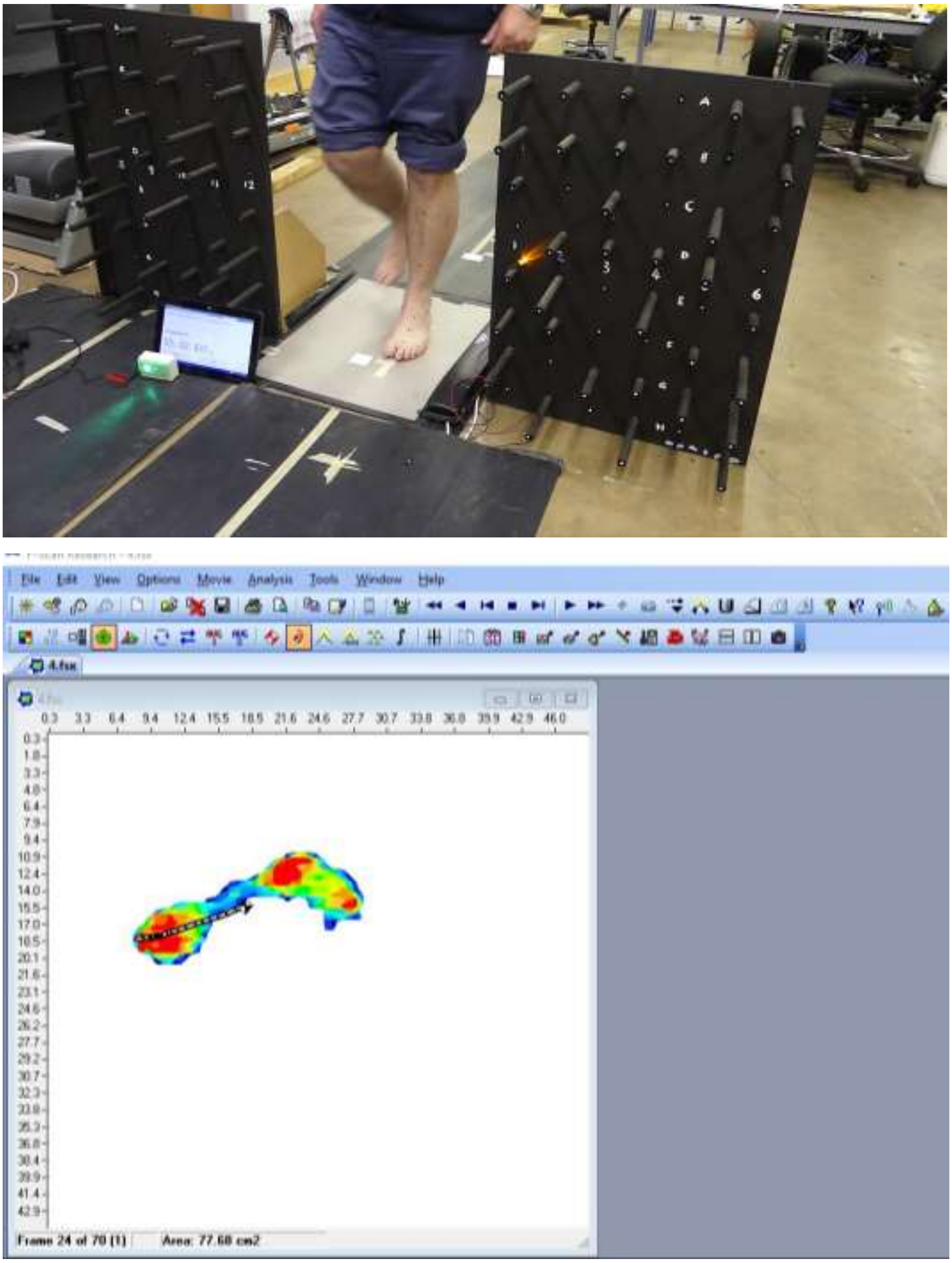

Figure 6.9: Photogrammetric system with the subject’s foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at mid-stance phase.

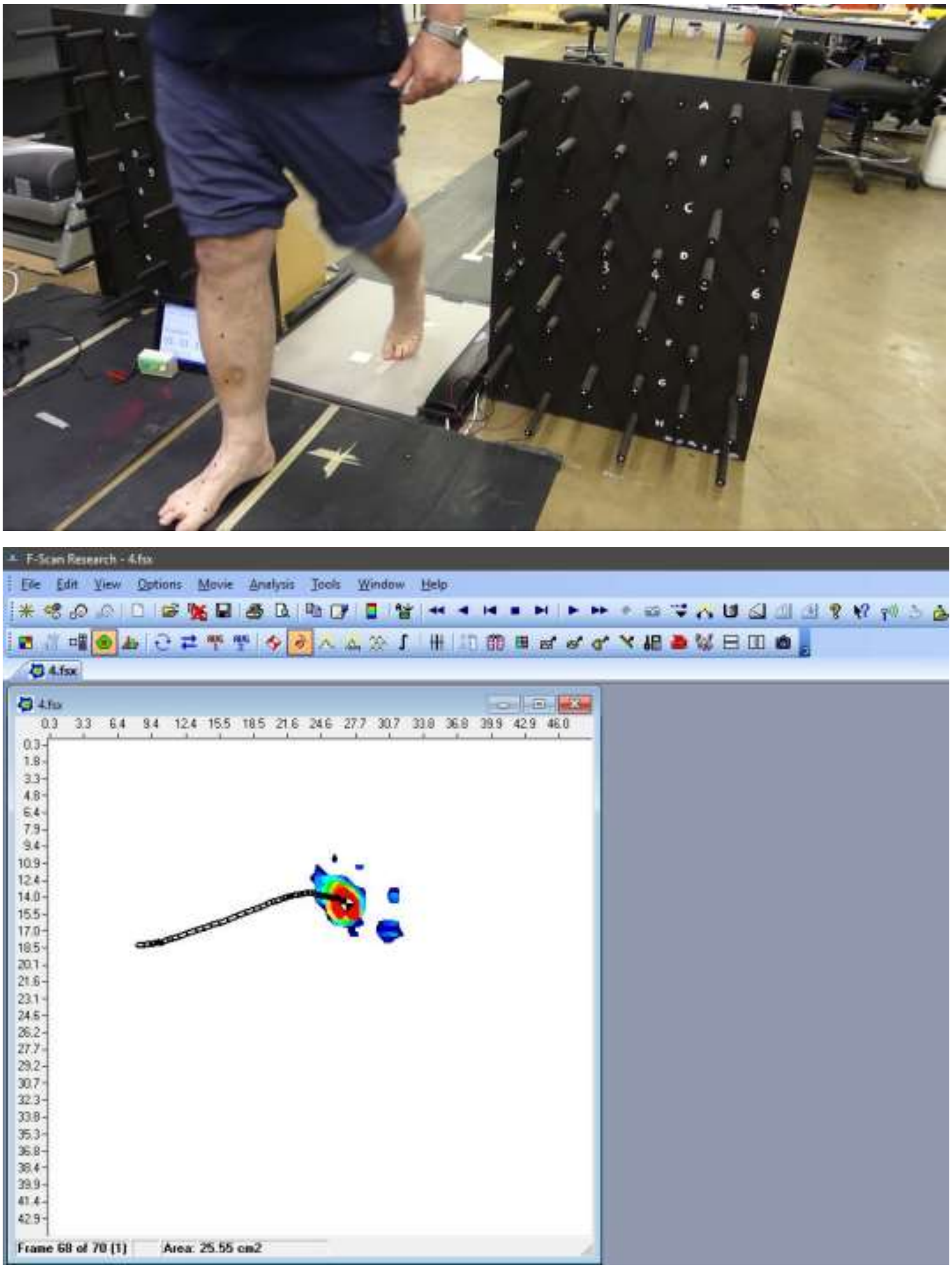

Figure 6.10: Photogrammetric system with the subject's foot on the pressure mat system along with the corresponding plantar pedobarographic image captured at toe-off phase.

6.4 Results, analysis, and discussion

Barefoot plantar pressures measured under dynamic conditions have been utilised as way to evaluate the foot in older adults, as elevated plantar pressure seems to be the major risk factor of the development of foot injuries. Injuries are the leading cause of foot complaints encountered by older people during the loading phase of gait (Burnfield et al., 2004; Bus and de Lange, 2005). The results of three repeated trials were collected for all selected subjects to obtain a reliable estimate of the actual values of contact area, contact pressure, and peak pressure for both cohorts: older adults, and adults as a control data. Three trials for obtaining gait test measurements were found to be sufficient to obtain the reliability necessary for clinical aspects in line with previous studies (Hughes et al., 1991; van der Leeden et al., 2004; Zammit et al., 2010). The subjects were requested to perform a two-step gait protocol (Bus and de Lange, 2005) to measure their plantar pressure parameters in a number of plantar regions.

The investigation involved innovative techniques to perform the correlation between human 3D gait phase images and the corresponding plantar pressure images. The research was carried out to examine foot rotation and loading based on integrating the human lower limb movement data with its corresponding plantar pressure data. The acquisition of the 3D models of human lower limb and foot was obtained utilising photogrammetric techniques whereas a set of plantar pressure data was acquired using the floor-based pressure mat system.

Five video cameras (Panasonic Lumix DMC-FZ300 Digital Camera) were utilised in the close-up photogrammetric multi stereo-video recording. Firstly, all five video cameras had to be calibrated. Table 6.1 presents the camera calibration parameters acquired by performing the self-calibration technique. Then, the calculation of the measurements of human lower limb movement was obtained for both older adults and adults by putting markers on subjects' lower limb and feet. The 3D measurements were computed by using off-the-shelf camera calibration software Australis®. The plantar parameters, such as contact area, contact pressure, peak pressure, and pressure-time integral were captured by a MatScan® (Tekscan, Boston, MA) plantar-pressure mapping system. The procedure was presented in detail in the methodology provided in section 6.3. Figure 6.11 shows: (a) the older individual's lower limbs and feet, displaying the two measurement systems adopted in the study; and (b) plantar pressure pedobarographic image, displaying the COP trajectory for the older adult. Generally, the investigation tests involved combining 3D lower limb movement measurements with plantar pressure data for both older adults and adult subjects as a control data. The outcome of these measurements was adopted to correlate the movements of the human lower limb with the corresponding plantar data.

Table 6.1: Camera calibration performed to obtain significant parameters, including the interior orientation parameters (PD, Xo, Yo), radial distortion parameters (K1, K2, K3), and the lens alignment parameters (P1, P2, B1, B2), for five video cameras (Panasonic Lumix DMC-FZ300 Digital Camera) adopted in the study.

	Camera 1	**Camera 2**	**Camera 3**	**Camera 4**	**Camera 5**
PD	4.4951	4.4582	4.3646	4.4185	4.4546
Xo	0.0506	0.0847	0.0404	0.0906	0.0628
Yo	0.1386	0.0369	0.0820	0.1058	0.0693
K1	3.25253e-003	3.12792e-003	1.95786e-003	2.25243e-003	3.32571e-003
K2	-8.96890e-004	-1.13775e-003	-3.64304e-004	-4.66033e-004	-1.38619e-003
K3	1.08522e-004	1.45743e-004	5.88641e-005	4.82845e-005	2.29675e-004
P1	-5.25693e-004	-9.71745e-004	-6.33880e-004	-9.90728e-004	-5.93224e-004
P2	-1.94476e-003	-1.94600e-003	-1.83604e-003	-1.60737e-003	-1.09370e-003
B1	3.33411e-003	9.73753e-003	3.42432e-003	1.37072e-003	3.08390e-003
B2	-7.32784e-005	1.45981e-003	-3.94526e-004	-2.79839e-004	2.85601e-004

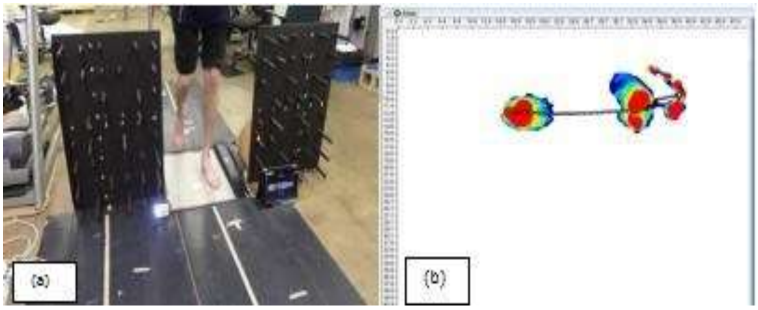

Figure 6.11: (a) Older Individual lower limbs and feet during gait with the two measurement systems: photogrammetric system and pressure mat system; (b) plantar pedobarographic image with the COP trajectory for an older adult.

The centre of pressure trajectory on the foot plantar surface represents a vector which defines the ground reaction force location points, passing from the hind foot to the forefoot (Chesnin et al., 2000; Fuchioka et al., 2015). The COP trace research has been adopted for balance control assessment during gait (Bizovska et al., 2014; Fuchioka et al., 2015; Han et al., 1999), and its relation to the risk of falls (Bizovska et al., 2014; Maki et al., 2006; Moghadam et al., 2011; Sole et al., 2017). Sole et al. (2017) determined the age-related effect on the centre of pressure path for a number of female participants during barefoot walking. The results revealed a positive correlation between the aging factor with the COP trajectory in the late stance phase, indicating that the COP was placed laterally with increasing human age. This could increase the risk of falling for older people (Maki and McIlroy, 2006). Furthermore, the study undertaken by Hessert et al. (2005b) has emphasised that older people were found to be weight bearing on their lateral side of the foot during gait, compared with young people. In contrast, a study conducted by Chiu et al. (2013) indicated a greater centre of pressure shift toward the medial side of the plantar surface during walking for older people. However, a study undertaken by Wong et al. (2008) stated that the COP shift toward either medial or lateral side of the plantar during barefoot walking can vary between individuals with regard to foot posture.

Generally, it has been shown that increased variability of COP has been associated with increased risk of falling for older adults (Piirtola et al., 2006; Rajachandrakumar et al., 2018). In addition, the COP trace characteristics have been utilised to provide an evaluation of gait performance for older adults (Chiu et al., 2013). Therefore, this study has both investigated the centre of pressure path for a number of older subjects and discussed its variation with the centre of pressure for adult subjects to study whether there is an association with instability during gait, which increase the risk of falling sustained with increasing age. In Figure 6.12, the foot COP trace for older individual 1 occurred during along the entire length of the foot, starting earlier from the heel-down position and continuing until the toe-off portion of the gait. The figure showed as well a small inclination of the COP trace starting from the area after the mid-foot portion, thus indicating that the older individual according to his age had no ability to keep the body balanced, in particular in the last phases of the stance phase of the gait cycle. Figure 6.13 presents the COP trace of the foot for older individual 2. In a similar way to individual 1, the trace started from a point before the whole heel-down process of touching the ground and continued centrally along the foot until the point of push-down phase. After a short period, the trace deflected to the right of the left foot and stopped in an area closer to the second metatarsal head.

Figure 6.14 shows the COP trace of older individual 3. It depicts that this older man had a better COP trace similar to an adult individual, starting earlier from a point before the heel-down and continuing with a central line along the entire length of the foot, having a tiny deflection from the second metatarsal point reaching to the farthest point of the hallux. Therefore, the three above-mentioned cases indicated that all parameters, such the difference in age, the way of walking, the weight, and the walking speed of each older individual have affected the COP trace and body balance for each one of them. Individual 3 had a better COP trace with less time walking from heel-strike to toe-off phases as he has taken 0.8 second to finish his stance phase of the gait cycle, which obviously was similar to an adult person. Individual 1, according to his foot structure having a small deformation in the hallux area took the longest time, 1.2 sec, to finish the stance phase. Individual 2 took 0.96 sec to accomplish his stance phase. Taking a longer time to finish the stance phase might be related to the need to maintain the balance loading for older adults while walking. In Figure 6.15, the COP trace extended from heel-strike to push-down in a continuous line with a slight lateral curve along the arch for an adult individual. The trace was centred along the heel, mid-foot, and the forefoot, thus indicating balanced loading. In addition, the COP trace moved from the central of forefoot area toward the area between the hallux and second toe, indicating normal push-down and toe-off phases for safe termination of the stance phase of the gait cycle.

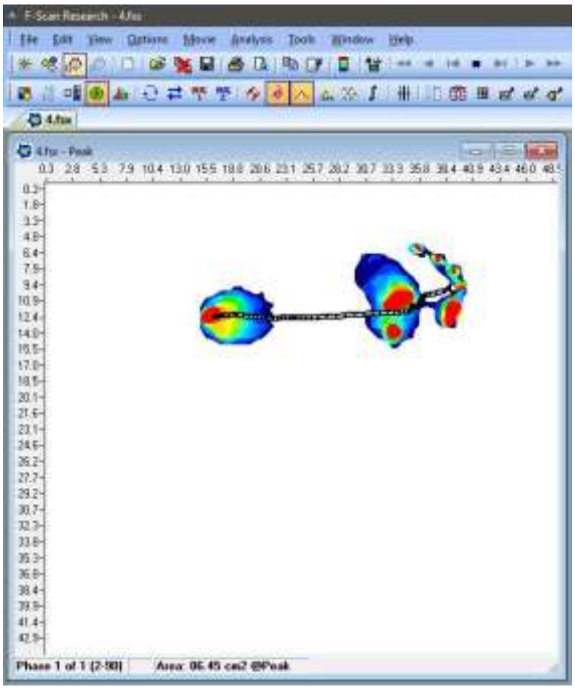

Figure 6.12: Foot pedobarographic image of older individual 1, showing the COP trajectory during the stance phase of the gait cycle.

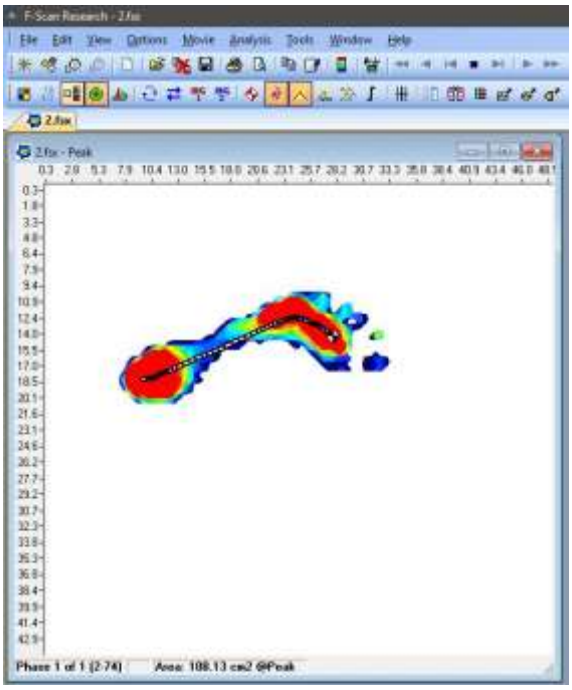

Figure 6.13: Foot pedobarographic image of older individual 2, showing the COP trajectory during the stance phase of the gait cycle.

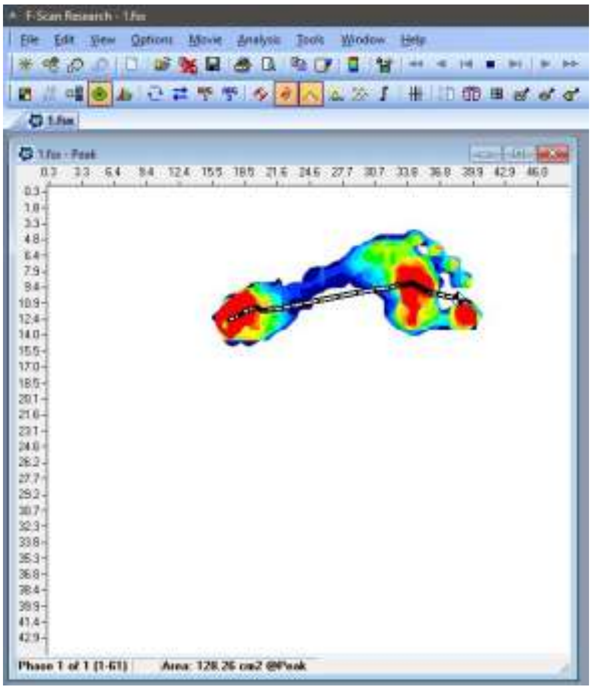

Figure 6.14: Foot pedobarographic image of older individual 3, showing the COP trajectory during the stance phase of the gait cycle.

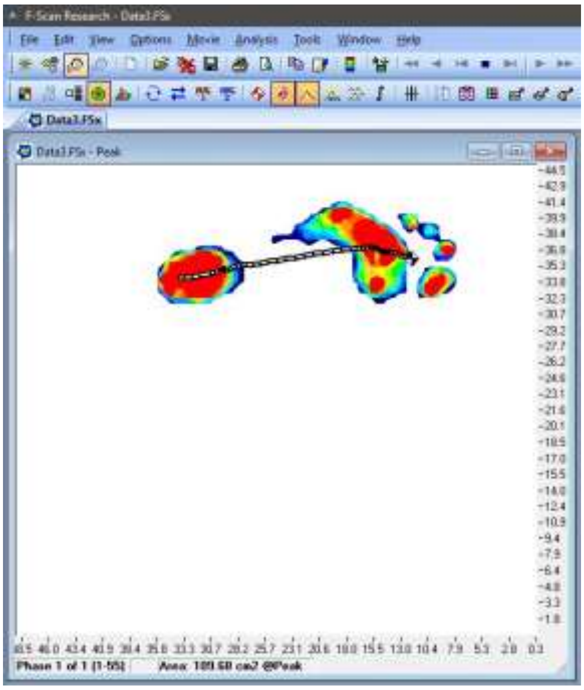

Figure 6.15: Foot pedobarographic image of an adult individual, showing the COP trajectory during the stance phase of the gait cycle.

Values for contact area, contact pressure, peak pressure, and pressure-time integral for older adult and adult groups are shown in Tables 6.2, and 6.3. There are noticeable differences in contact pressure parameters in between the three older individuals in many of the seven foot regions measured for the entire stance phase. The contact pressure showed a huge difference between subject 1 and 2 in all foot regions selected in the study. The results revealed higher contact pressure and peak pressure values at hallux and lesser-toes regions for subject 1 relative to the results of subject 2. In contrast, the rest of the foot regions had lower contact pressure and peak pressure measures for subject 1 compared to the same parameters recorded for subject 2.

Obviously, the contact area value of the total foot measured during the whole stance phase of the gait cycle for subject 1 was lower than the other two subjects due to the foot shape changes apparently occurring with advancing age accompanied by the fact that the subject had a curved foot, resulting in a less contact area with the floor mat at the total plantar surface of the foot and in particular under the mid-foot area. The contact area value for the total foot for subject 1 was 86.45 cm^2 while for subjects 2, and 3 they were (108.13, 128.26 cm^2), respectively. Furthermore, the contact area values beneath the mid-foot region for subject 1 was 1.81 cm^2 whereas these measures were (20.9, 20.13 cm^2) for subject 2, and 3, respectively. These measures can be seen from the plantar pedobarographic images for the three subjects presented in Figures 6.12, 6.13, and 6.14. In contrast, subject 2 had lower contact area value at the hallux region as the subject had a severe deformation at the toes region, which caused rotation in the lower limb, thus giving less contact area with the mat floor at this region. The subject recorded the highest contact pressure and peak pressure at the forefoot region compared with the other two subjects, particularly under the lateral forefoot area as a result of his way of walking. It seems that this older subject had to bear the body weight on his forefoot region, specifically the lateral side, as a way to maintain the body balance during gait. The peak pressure value at the lateral forefoot region for subject 2 was 1139 kpa while these values for subject 1, and 3 were (327, 201 kpa), respectively, potentially placing this region at the risk of developing foot injuries as has previously been mentioned.

Subject 3 had the highest total foot contact area along the entire stance phase of the gait cycle, which was 128.26 cm^2 as a result of his stability during walking, observed during the gait test on the pressure mat, thus showing a linearly stable COP trace with more area contacted the mat as displayed in Figure 6.14. It is worth noting that the maximum contact pressure value in the hallux and lesser-toes regions was (398, 231 kpa), respectively for subject 1. In the medial and lateral forefoot regions, the maximum values were (401, 428 kpa) for subject 2; furthermore, the highest contact pressure for the total foot along the whole stance phase amongst the subjects was recorded for subject 2, which recorded a value of 390 kpa.

Relatively, the large differences for pressure-time integral in the plantar regions among the three older subjects were caused by the difference in the pressures distributed, and the contact time spent to finish the stance phase from heel-strike until the toe-off phases. The highest pressure-time integral located at the hallux and lesser-toes regions was recorded for subject 1. The pressure-time integral values in both medial and lateral forefoot regions were higher for subject 1 and 2 compared to subject 3. The trend toward a longer contact time from subject 1, and 2 accompanied by higher pressures for most of the foot regions had resulted in higher values of the pressure-time integral at the total foot area measured for the whole stance phase, which were (184.43, 229.11 kpa*sec), respectively compared with the one recorded for subject 3, which was 81.72 kpa*sec. The contact time taken to finish the stance phase of the gait cycle for subject 1, 2, and 3 was (1.17, 0.96, and 0.8 sec), respectively whereas for adult subject 1, 2, and 3 was (0.73, 0.84, and 0.72 sec), respectively.

The results pointed out that older subject 3 showed close gait patterns with the adult subjects with clear similarity in the values of pressure distributed under the plantar regions. The deflection in the COP trace from the forefoot area toward the hallux area for this subject indicated a stable termination for the stance phase. However, the inclination of the COP trace for older subject 2 toward the lateral forefoot region to end in a point close to the second metatarsal head gave an impression about the amount of pressure parameters distributed on the hallux, which was the smallest for both pressure and contact area values because of the rotation of the left foot to the left side during the loading phase of gait. The plantar pressure distribution measurements captured for adults participating in the study beneath the seven foot regions measured for the entire stance phase of the gait cycle showed close recordings in plantar parameters regardless of a number of consistent disparities. The discrepancies observed from the plantar pressure patterns in selected adult subjects appeared to rely on the way of walking and gait characteristics for each adult individually. The result exhibited a linear stable COP trajectory along the entire plantar surface for an adult subject, as displayed in Figure 6.15.

Table 6.2: Plantar pressure parameters measured for three older individuals during the whole stance phase of the gait cycle under seven foot regions.

Contact area in (cm^2)	**subject 1**	**subject 2**	**subject 3**
Hallux	7.23	3.87	8.26
Lesser-toes	8.77	9.29	11.35
Medial forefoot	20.9	20.39	32.26
Lateral forefoot	18.06	21.68	25.03
Mid-foot	1.81	20.9	20.13
Heel	28.39	31.74	29.16
Total foot	86.45	108.13	128.26
Contact pressure in (kpa)			
Hallux	398	55	168
Lesser-toes	231	120	79
Medial forefoot	240	401	183
Lateral forefoot	141	428	103
Mid-foot	26	120	40
Heel	191	443	176
Total foot	230	390	151
Peak pressure in (kpa)			
Hallux	906	61	267
Lesser-toes	475	186	135
Medial forefoot	853	917	605
Lateral forefoot	327	1139	201
Mid-foot	35	255	68
Heel	586	867	565
Total foot	906	1139	605
pressure-time integral in (kpa*sec)			
Hallux	261.04	7.97	45.52
Lesser-toes	94.22	42.12	31.88
Medial forefoot	165.67	115.81	77.54
Lateral forefoot	72.42	201.07	51.42
Mid-foot	7.64	51.58	8.75
Heel	78.96	144.13	39.14
Total foot	184.43	229.11	81.72

Table 6.3: Plantar pressure parameters measured for three adult individuals during the whole stance phase of the gait cycle under seven foot regions.

Contact area in (cm^2)	**subject 1**	**subject 2**	**subject 3**
Hallux	8.26	10.32	9.03
Lesser-toes	4.13	5.94	9.29
Medial forefoot	21.94	23.48	27.1
Lateral forefoot	21.16	20.39	23.23
Mid-foot	9.81	7.23	7.48
Heel	29.16	31.74	33.29
Total foot	94.19	99.1	109.68
Contact pressure in (kpa)			
Hallux	390	411	185
Lesser-toes	198	434	96
Medial forefoot	291	293	159
Lateral forefoot	226	196	167
Mid-foot	48	64	35
Heel	341	399	268
Total foot	300	393	204
Peak pressure in (kpa)			
Hallux	692	896	543
Lesser-toes	455	873	253
Medial forefoot	835	1002	480
Lateral forefoot	476	442	419
Mid-foot	54	102	58
Heel	888	1331	542
Total foot	888	1331	543
pressure-time integral in (kpa*sec)			
Hallux	62.6	101.4	48
Lesser-toes	36.2	116.4	26.9
Medial forefoot	99.1	115.1	55.7
Lateral forefoot	77.1	59.8	68.2
Mid-foot	14	23.2	13.9
Heel	93.7	124	80.1
Total foot	151.5	196.6	88.2

Table 6.4, and Table 6.5 show the data captured for older adults and adults. This included the knee cap (KC) photogrammetric coordinates, and COP trajectories at heel-strike (HD), mid-stance (MS), and push-off (PO) phases. The data presented in these tables has been adopted to study the correlation between the lower limb movement and the plantar pressure for older adults and adult subjects and this is shown in Figures 6.16, 6.17, 6.18, 6.19, 6.20, and 6.21. Figure 6.16 depicts the correlation

between lower limb movement measurements obtained by photogrammetric techniques and plantar pressure data. The medial foot axis (MFA) represented the line between COP position at heel area and the second metatarsal bone point under the foot. The plot showed the relative position of the major COP excursions (heel-strike, mid-stance, and push-off) with the corresponding knee cap position at these three main phases of the gait cycle for a left barefoot gait trial of older adult 1. The point label "_F" and "_K" indicated the foot and knee cap position, respectively. It is supposed that there is an alignment between the trajectories of the knee cap positions with the medial foot axis, thus providing the required support for the human body during gait phases.

For the left foot trial, the MS_F was away from the medial foot axis (MFA) for older adults 2, and 3, and that is shown in Figures 6.17, and 6.18, respectively. In addition, the KC trajectory was not aligned with MFA for all selected older adults. However, the KC was aligned with MFA line for adult subjects and this is shown in Figures 6.19, 6.20, and 6.21, which depict the relative position of the major COP excursion locations at main phases of the gait cycle with the corresponding knee cap position for normal human gait represented by adult subject gait. This suggests that the gait performance of adults is optimal by allowing the KC trajectory within the footprint on the ground, thereby granting more body balance and support during gait. Moreover, the fact that COP at MS_F being closer to the KC trajectory provides more body balance for adults' gait, thus avoiding rotation or falling cases suffered by older adults. Additionally, the correlation technique showed that the obtained knee offset measurements in the x-direction computed for older subjects were higher than that for the adult subjects, as shown in Tables 6.4, and 6.5. This indicated that older adults' knee had to travel a bigger distance in between the loading phases of the gait cycle, as seen in Figures 6.16, 6.17, and 6.18.

Figures 6.19, 6.20, and 6.21 show the correlation between human lower limb movements and plantar pressure measurements for adult subjects, depicting the relative position of the major COP excursion locations at main phases of the gait cycle with the corresponding knee cap position for normal human gait represented by adult subject gait. In these figures, it has shown that there is an alignment between the trajectories of the knee cap positions with the medial foot axis, thus providing the required support for the human body during gait phases.

For the left foot trial for selected adult subjects, the MS_F was close the medial foot axis (MFA), thus providing more body balance for normal gait performed by adult people. In addition, the KC trajectory was aligned with MFA line for all selected adult subjects, which allows the KC trajectories to be within their footprint on the ground. This can enhance the gait performance through providing the required body balance and support while movement. Moreover, the correlation technique showed that the obtained knee offset measurements in the x-direction computed for adult subjects were smaller than that for the older subjects, indicating normal knee travel in between the loading phases of the gait cycle for adult subjects.

This research provided high accuracy in relation to positional changes of human lower limbs and feet during normal gait through adopting 3D multi-stereo photogrammetric techniques. The photogrammetric technique involved in this research was beneficial in terms of interpretation of the knee joint movement, which contributed to enhance the perceiving of the older adults' gait performance and changes occurring with advancing age. The research developed correlation techniques of new gait analysis methods of the lower limb and foot with corresponding plantar data for older people. The measurements of the developed technique obtained by the two adopted systems during loading phases of gait can ultimately achieve the aim of the research.

Table 6.4: 3D lower limb and foot measurements along with plantar pressure data among three main phases of the gait cycle for older subjects.

		older adult-left barefoot measurements			
		heel-strike	mid-stance	push-off	2nd metatarsal
subject 1	COP position (x, y in mm)	61.46,194.54	51.86,193.54	43.56,191.54	43.86,192.54
	knee cap position (x, y in mm)	67.68,192.98	47.21,194.61	22.96,195.15	
	knee offset (x, y in mm)				30.76,186.74
subject 2	COP position (x, y in mm)	66.59,191.36	57.39.188.96	47.59,187.26	48.39,188.86
	knee cap position (x, y in mm)	69.72,188.08	56.3,190.43	32.01,193.11	
	knee offset (x, y in mm)				27.79,179.06
subject 3	COP position (x, y in mm)	53.74,196.85	46.34,195.25	37.24,194.05	38.24,194.85
	knee cap position (x, y in mm)	57.85,193.28	39.77,195.6	24.04,197.36	
	knee offset (x, y in mm)				24.64,188.95

Table 6.5: 3D lower limb and foot measurements along with plantar pressure data among three main phases of the gait cycle for adult subjects.

		adult-left barefoot measurements			
		heel-strike	mid-stance	push-off	2nd metatarsal
subject 1	COP position (x, y in mm)	42.1,206.1	31.9,205.3	24.4,203.1	25.3,201.9
	knee cap position (x, y in mm)	48.5,203.1	33.4,203.4	11.5,206	
	knee offset (x, y in mm)				9.3,189.7
subject 2	COP position (x, y in mm)	51.5,217.7	39.7,202.6	32.4,201.7	33.3,189.4
	knee cap position (x, y in mm)	54.8,194.2	46.2,195.7	22.6,196.5	
	knee offset (x, y in mm)				13.2,177.7
subject 3	COP position (x, y in mm)	46.3,205.6	36,204.40	26.8,203	33.2,202
	knee cap position (x, y in mm)	66.91,207.2	55.94,206.96	26.77,206.26	
	knee offset (x, y in mm)				14.5,199.5

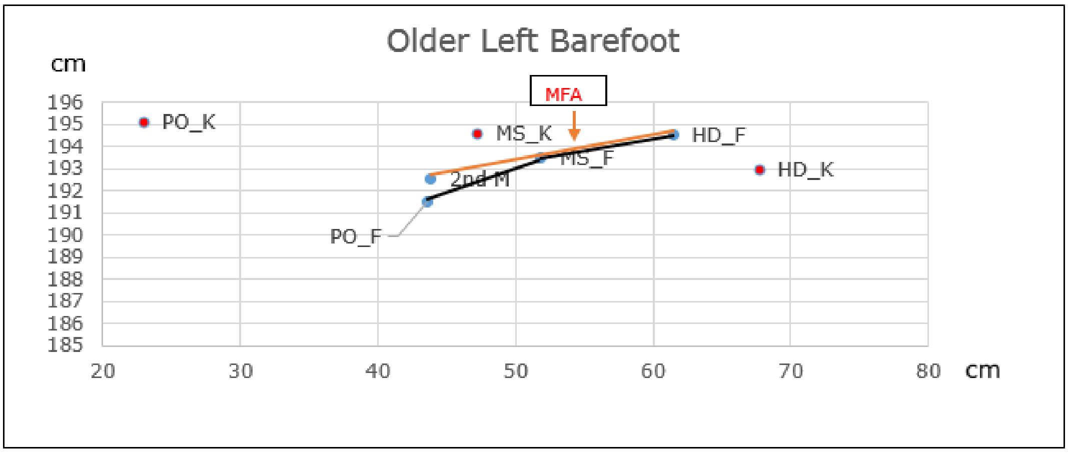

Figure 6.16: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for older subject 1.

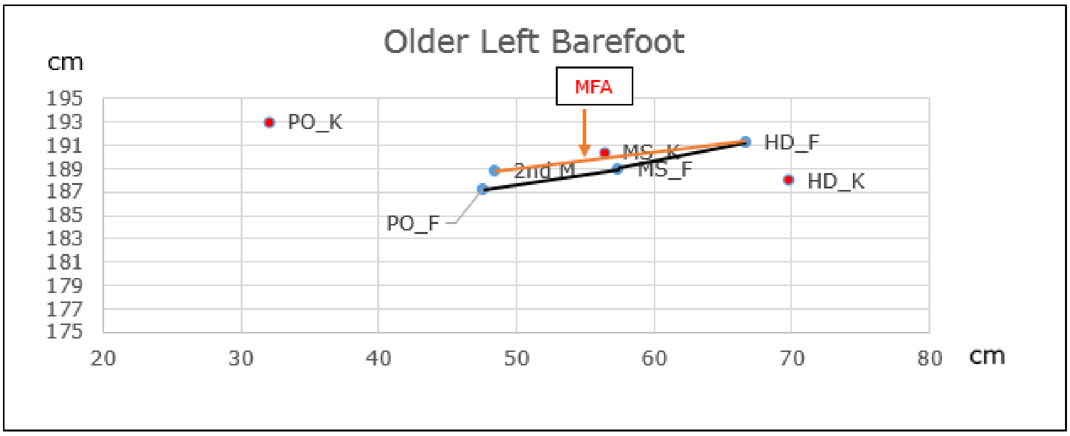

Figure 6.17: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for older subject 2.

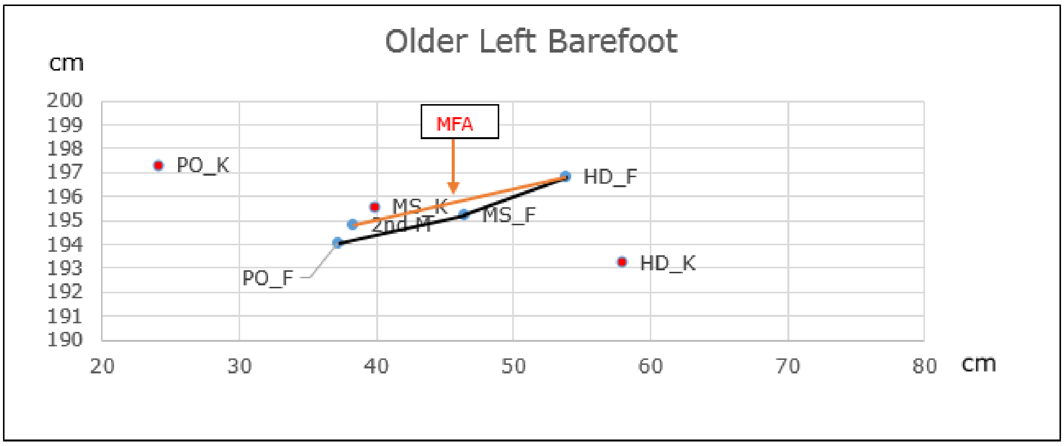

Figure 6.18: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for older subject 3.

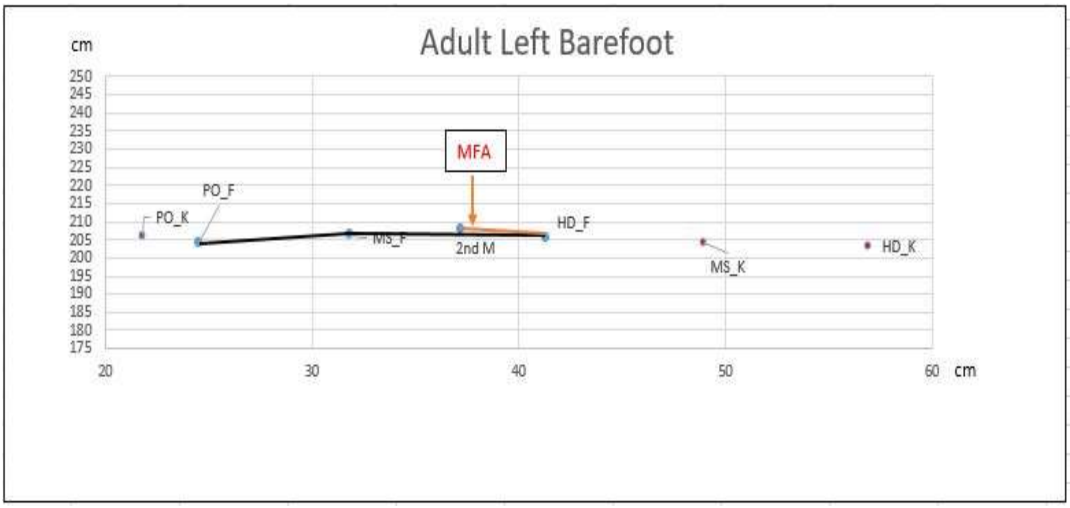

Figure 6.19: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for an adult subject 1.

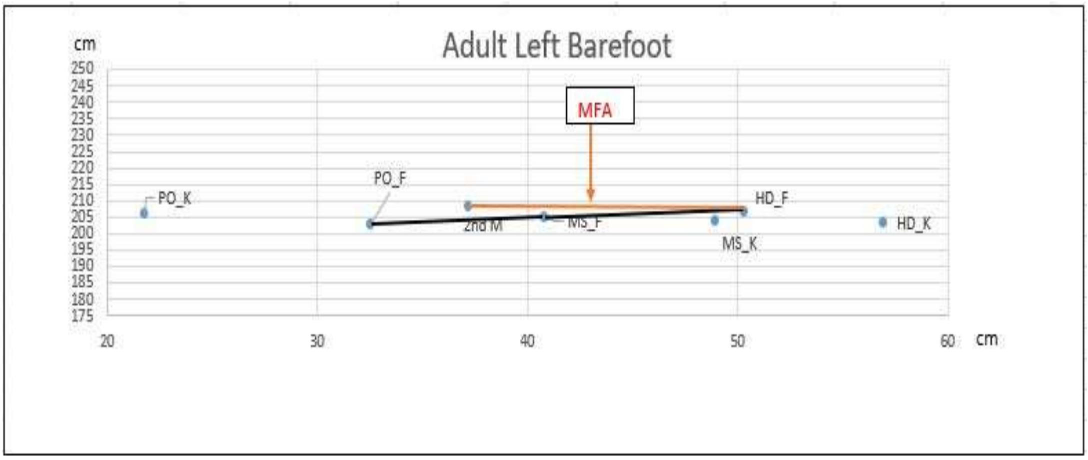

Figure 6.20: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for an adult subject 2.

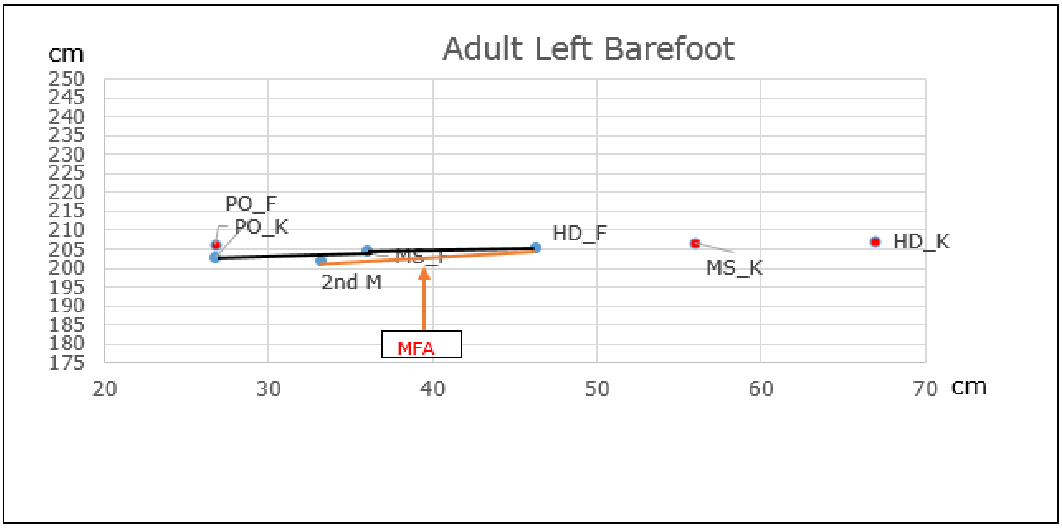

Figure 6.21: Plot of the COP trajectory and knee position of the barefoot gait at three main phases of the gait cycle for an adult subject 3.

6.5 Conclusion

A high accuracy correlation technique of 3D lower limb and foot movement and centre of pressure excursion was developed in the current research. The newly developed correlation technique assisted in providing an evaluation of the gait trial based on barefoot older adults and adult subjects. The 3D model of the human lower limb using photogrammetric techniques was valuable as it enhanced the visualisation of human movement for both cohorts participating in the study: older adults and adults. As a consequence, a new insight into possible changes occurring due to the aging factor has been improved. The new measurements obtained in the present research could assist in finding the optimal footwear design necessary to compensate for age-related balance deficiencies and to diminish foot complaints encountered by older people while in the loading phase of gait. The study suggested that clinical interventions or even designed suitable soles of shoes based on the research outcomes would be essential to avoid developing foot complaints sustained with advancing age.

CHAPTER SEVEN

CONCLUSION AND FUTURE RESEARCH RECOMMENDATIONS

7.1 General conclusion

The variation in dynamic plantar pressure patterns between healthy older adults and adults was examined in chapter three. The study was designed to highlight the gait pattern changes between the two cohorts during normal walking. The gait pattern changes permitted an understanding of the reasons beyond foot complaints sustained with advancing age during the entire stance phase of the gait cycle. The plantar pressure distribution was evaluated under five anatomically defined foot regions: whole foot, heel, mid-foot, forefoot, and the hallux, while the subjects were wearing pressure sensor insoles. Furthermore, plantar pressure parameters, analysed based on the average weight for each group, were assessed to study whether including the weight factor had implications for plantar pressure pattern comparisons undertaken between the two participating groups. Forty subjects were recruited in this investigation to perform the gait tests during walking on level surfaces at their self-selected speed. The findings were as follows:

1. Higher plantar pressure measurements were located for the older adults group under a number of plantar regions, except the mid-foot region, which showed lower measures in plantar parameters, compared to the adults group.
2. Taking into consideration the percentage of the averaged weight for each specific group, an analysis of plantar pressure parameters demonstrated similar results to those conducted to the initial measured data. However, there were a small number of variations in the amounts of the difference in pressure parameters between the two participating groups: older adults and adults, compared to original comparisons for initial captured data.

This investigation led to further beneficial aspects:

1. The plantar pressure distribution measured during the whole stance phase of the gait cycle thoroughly enhanced the plantar pressure patterns visualisation

of the entire plantar surface. This visualisation assisted in improving an insight into gait pattern changes due to the aging factor. The new insight contributed to better understanding of the foot problems for older people while moving.

2. The plantar loading distribution measurements should be valuable to use as a reference value to compare them with various gait pathologies sustained with advancing age.
3. This investigation could be intrinsic to the clinical arena for either assessment or for finding treatment strategies for various foot complaints occurring during gait. These complaints predominantly develop for older people; hence, the investigation could help to avoid a number of foot problems that may develop due to advancing age.
4. The study provides an evaluation of the gait while adopting in-shoe pressure sensor systems for older adults with the control data: the adult individuals. Providing comprehensive understanding of the pressure parameters can assist in supporting older adults through designing foot wear optimised to suit their needs in order to improve their quality of life.

The measurements of plantar loading patterns under the human foot plantar for a group of older adults during various gait conditions were taken while walking on level surfaces, uphill and downhill walking steps, while the subjects were wearing in-shoe pressure sensor insoles. These measurements were examined in chapter four. Studying the influence of these tasks on the balance of the body and stability with advancing age was also discussed in this investigation. Twenty healthy older adults were recruited in this research to perform gait trials for the three above mentioned tasks. The subjects performed the gait trials at their self-selected speeds using pressure insoles as a measurement system for capturing plantar pressure measurements. The pressure parameters were collected under five foot plantar regions: whole foot, heel, mid-foot, forefoot, and the hallux. The findings were as follows:

1. The plantar parameters, including contact pressure, peak plantar pressure, force-time integral, and pressure-time integral measures, in particular underneath the whole foot, forefoot, and hallux areas were higher for uphill walking conditions compared to walking on level surfaces. In contrast, the

contact area values were lower under these regions for uphill walking conditions compared to walking on level surfaces.

2. An excessive increase in a number of plantar parameters: peak pressure, force-time integral, and pressure time integral, was detected beneath the whole foot, forefoot, and hallux regions for downhill walking conditions in relation to those of level walking conditions.

This investigation had further beneficial aspects:

1. Measuring plantar parameters underneath the foot plantar enabled a comprehensive examination of the distribution of the human body weight for a group of older adult subjects. The evaluation of plantar pressure patterns provided for older people during various walking tasks enhanced the visualisation of the plantar pressure values distributed underneath the entire plantar surface. The new visualisation can contribute to a clear understanding of the body balance deficiencies associated with each of these walking activities.
2. The measurements of plantar pressure distribution analysed for a number of older adult individuals provided a gait assessment during different tasks. These measurements can be useful to use as standard values for the clinical settings for the diagnosis of gait problems and for the treatment of foot injuries for older people in relation to these walking activities.
3. Understanding the discrepancies in plantar loading patterns for uphill and downhill walking conditions in relation to horizontal walking on level surfaces, which might be the reasons for a loss of balance and instability during walking, can provide foot wear design to suit the need of older adults to minimise the falling risk during walking on inclined surfaces.

The evaluation of plantar loading patterns for older adults and adults during the stance phase of the gait cycle, in particular at: heel-strike, foot-flat, mid-stance, push-down, and toe-off phases distributed under fifteen plantar regions was investigated in chapter five. The plantar regions: medial heel, lateral heel, medial mid-foot, lateral mid-foot, medial forefoot, lateral forefoot, metatarsal (1, 2, 3, 4, and 5), and toe (1, 2, 3, 4, and 5) were selected in the study to measure plantar pressure parameters while the subjects were performing barefoot walking using floor-based pressure mat systems. The study aimed to find out whether foot problems and instability of walking encountered with advancing age have been associated with specific selected phases where the foot is in contact with the ground during locomotion. These issues were evaluated using plantar pressure patterns for older adults in comparison with adult subjects. Furthermore, chapter five also provided an analysis of plantar pressure parameters during single limb support intervals, taking into account the body weight of participating subjects and the stance phase duration taken by them.

The investigations led to a number of findings, which were as follows:

1. Higher contact pressures and peak pressures were revealed for older adults, in particular during the mid-stance, push-down, and toe-off phases, compared to the adults' group. These values were located at the forefoot region, specifically under the metatarsal heads and the hallux regions. This means that, for people of older age, the metatarsal heads and the hallux would be considered as vulnerable regions among the entire plantar surface of human foot during the loading phase of gait.
2. Taking into consideration the weight and time with analysing plantar parameters, in particular during single limb support intervals showed similar comparisons relative to comparisons conducted to initial analysed parameters. The analysis of plantar pressure parameters based on the weight and time emphasised the fact that higher measures of contact pressure and peak pressure were located under most of the selected foot regions for the older adults' group relative to the group of adult subjects.

Additionally, chapter six investigated an innovative technique based on integrating lower limb movement with plantar pressure data to perform the correlation between both of them. The human 3D gait phase images were obtained using photogrammetric techniques, whereas the centre of pressure traces were acquired using floor-based pressure mat systems. The integrated data was used to identify the variations in gait characteristics between the two participating cohorts: older adults and adult individuals, for the examination of foot rotation and loading during the heel-strike, mid-stance, and toe-off phases of gait. The variations were identified while the subjects were performing typical barefoot walking using the two-step gait initiation protocol. A high-accuracy correlation technique of human 3D lower limb movement and the centre of pressure trajectories during the loading phase of gait, particularly during heel-strike, mid-stance, and toe-off phases, was developed. This correlation permitted new comparison and evaluation of the gait study based on barefoot walking conditions between the two groups participating in the study: older adults and adults.

7.2 Future directions of the research

This research may address a number of future investigations, which will be illustrated in the following points:

1. The plantar pressure distribution measurements used in this study allow for clear interpretation of the gait characteristics for a number of healthy individuals. Future investigations could involve people with gait pathologies and people with foot deformities. Accordingly, the plantar regions should be selected in accordance with the more affected plantar regions in association with each investigated foot condition.
2. The current investigation involves the comparisons of various walking conditions: level walking, and uphill and downhill walking, performed by a number of older adults; however, future work could involve expanding the collection of plantar pressure parameters for the older adults group to include more walking activities. These comprised stair ascending and descending, which can provide a comprehensive information of the gait characteristics for these two tasks, along with their comparisons to walking on level surfaces.
3. The plantar pressure data collection method could involve the determination of the gait parameters during various walking speeds for different walking tasks. Different gait speeds can influence the plantar pressure patterns, in particular among older communities. This determination may lend substantial insights into safe and appropriate speeds to be adopted by older people during various gait activities.
4. Future work could involve 3D models of the whole lower limb, correlated with the centre of pressure trajectories during movement. The correlations may provide substantial insight for the interaction of human lower limb movement with plantar pressure data during the main phases of loaded gait.

5. Developing the correlation technique to capture more details about the interactions of human lower limb movements with the plantar surface can be implemented. This can potentially be beneficial for applications of manufacturing footwear. In particular, the benefits can apply to those dedicated to the needs of older people during the loading phase of gait.

REFERENCES

Abdelkrim, N.B., El Fazaa, S. and El Ati, J., 2007. Time–motion analysis and physiological data of elite under-19-year-old basketball players during competition. *British Journal of Sports Medicine* 41(2), 69-75.

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

Abouaesha, F., van Schie, C.H., Griffths, G.D., Young, R.J. and Boulton, A.J., 2001. Plantar tissue thickness is related to peak plantar pressure in the high-risk diabetic foot. *Diabetes care* 24(7), 1270-1274.

Abri, H., Aalaa, M., Sanjari, M., Amini, M.R., Mohajeri-Tehrani, M.R. and Larijani, B., 2019. Plantar pressure distribution in diverse stages of diabetic neuropathy. *Journal of Diabetes & Metabolic Disorders*, 1-7.

Ahroni, J.H., Boyko, E.J. and Forsberg, R., 1998. Reliability of F-scan in-shoe measurements of plantar pressure. *Foot & ankle international* 19(10), 668-673.

Ahroni, J.H., Boyko, E.J. and Forsberg, R.C., 1999. Clinical correlates of plantar pressure among diabetic veterans. *Diabetes care* 22(6), 965-972.

Akhlaghi, F., Pepper, M., Daw, J. and Potter, M., 1994. In-shoe step-to-step pressure variations. *The foot* 4(2), 62-68.

Al-Baghdadi, J., Chong, A., Alshadli, D., Milburn, P. and Newsham-West, R., 2013a. Plantar surface contour using close range photogrammetry. *Footwear Science* 5(sup1), S15-S16.

Al-Baghdadi, J.A.A., Chong, A.K., McDougall, K., Alshadli, D., Milburn, P. and Newsham-West, R. 2011 A dense surface modelling technique for foot surface imaging, pp. 295-302, Scion.

AL-Baghdadi, J.A.A., Chong, A.K., McDougall, K., Milburn, P. and Newsham-West, R. 2013b Human foot plantar surface shape change during gait, pp. 1-4, National Taiwan Normal University.

Alexander, N. and Schwameder, H., 2016. Effect of sloped walking on lower limb muscle forces. *Gait & posture* 47, 62-67.

Allet, L., Armand, S., de Bie, R.A., Pataky, Z., Aminian, K., Herrmann, F.R. and de Bruin, E.D., 2009. Gait alterations of diabetic patients while walking on different surfaces. *Gait & posture* 29(3), 488-493.

Alshadli, D., Chong, A.K., McDougall, K., Ahmed, J. and Ali, A.-B. 2011 Skin texture-enhancement for automated 3D point cloud generation in charcot-marie-tooth disease application, pp. 6-10, IEEE.

Amemiya, A., Noguchi, H., Oe, M., Ohashi, Y., Ueki, K., Kadowaki, T., Mori, T. and Sanada, H., 2014. Elevated plantar pressure in diabetic patients and its relationship with their gait features. *Gait & posture* 40(3), 408-414.

Amstutz, E., Teshima, T., Kimura, M., Mochimaru, M. and Saito, H. 2008 PCA based 3D shape reconstruction of human foot using multiple viewpoint cameras, pp. 161-170, Springer.

Antunes, P., Dias, G., Coelho, A., Rebelo, F. and Pereira, T., 2008. Non-linear finite element modelling of anatomically detailed 3D foot model. *Report paper*, 1-11.

Armstrong, D.G. and Lavery, L.A., 1998. Elevated peak plantar pressures in patients who have Charcot arthropathy. *JBJS* 80(3), 365-369.

Awale, A., Hagedorn, T.J., Dufour, A.B., Menz, H.B., Casey, V.A. and Hannan, M.T., 2017. Foot function, foot pain, and falls in older adults: the Framingham foot study. *Gerontology* 63(4), 318-324.

Aydos, L., Uzun, A., Kaya, M., Kanatli, U., Esen, E. and Uslu, S., 2012. The effect of volleyball on the sole contact areas and maximal forces of female volleyball players. *SCIENTIFIC JOURNAL OF SPORT AND PHYSICAL EDUCATION*, 4.

Bacarin, T.A., Sacco, I.C. and Hennig, E.M., 2009. Plantar pressure distribution patterns during gait in diabetic neuropathy patients with a history of foot ulcers. *Clinics* 64(2), 113-120.

Barisch-Fritz, B., Schmeltzpfenning, T., Plank, C. and Grau, S., 2014. Foot deformation during walking: differences between static and dynamic 3D foot morphology in developing feet. *Ergonomics* 57(6), 921-933.

Barn, R., Waaijman, R., Nollet, F., Woodburn, J. and Bus, S.A., 2015. Predictors of barefoot plantar pressure during walking in patients with diabetes, peripheral neuropathy and a history of ulceration. *PLoS One* 10(2), e0117443.

Bautmans, I., Jansen, B., Van Keymolen, B. and Mets, T., 2011. Reliability and clinical correlates of 3D-accelerometry based gait analysis outcomes according to age and fall-risk. *Gait & posture* 33(3), 366-372.

Beauchet, O., Allali, G., Annweiler, C., Bridenbaugh, S., Assal, F., Kressig, R.W. and Herrmann, F.R., 2009. Gait variability among healthy adults: low and high stride-to-stride variability are both a reflection of gait stability. *Gerontology* 55(6), 702-706.

Beauchet, O., Allali, G., Sekhon, H., Verghese, J., Guilain, S., Steinmetz, J.-P., Kressig, R.W., Barden, J.M., Szturm, T. and Launay, C.P., 2017. Guidelines for assessment of gait and reference values for spatiotemporal gait parameters in older adults: the biomathics and Canadian gait consortiums initiative. *Frontiers in human neuroscience* 11, 353.

Berg, W.P., Alessio, H.M., Mills, E.M. and Tong, C., 1997. Circumstances and consequences of falls in independent community-dwelling older adults. *Age and ageing* 26(4), 261-268.

Bergstra, S., Kluitenberg, B., Dekker, R., Bredeweg, S., Postema, K., Van den Heuvel, E., Hijmans, J. and Sobhani, S., 2015. Running with a minimalist shoe increases plantar pressure in the forefoot region of healthy female runners. *Journal of Science and Medicine in Sport* 18(4), 463-468.

Bertsch, C., Unger, H., Winkelmann, W. and Rosenbaum, D., 2004. Evaluation of early walking patterns from plantar pressure distribution measurements. First year results of 42 children. *Gait & posture* 19(3), 235-242.

Bhatt, T., Espy, D., Yang, F. and Pai, Y.-C., 2011. Dynamic gait stability, clinical correlates, and prognosis of falls among community-dwelling older adults. *Archives of physical medicine and rehabilitation* 92(5), 799-805.

Birtane, M. and Tuna, H., 2004. The evaluation of plantar pressure distribution in obese and non-obese adults. *Clinical Biomechanics* 19(10), 1055-1059.

Bizovska, L., Svoboda, Z., Kutilek, P., Janura, M., Gaba, A. and Kovacikova, Z., 2014. Variability of centre of pressure movement during gait in young and middle-aged women. *Gait & Posture* 40(3), 399-402.

Blake, A., Morgan, K., Bendall, M., Dallosso, H., Ebrahim, S., Arie, T.a., Fentem, P. and Bassey, E., 1988. Falls by elderly people at home: prevalence and associated factors. *Age and ageing* 17(6), 365-372.

Blenkinsopp, R., Harland, A., Price, D., Lucas, T. and Roberts, J., 2012. A method to measure dynamic dorsal foot surface shape and deformation during linear running using digital image correlation. *Procedia Engineering* 34, 266-271.

Bongi, S.M., Del Rosso, A., Mikhaylova, S., Landi, G., Ferretti, B., Cavigli, E., Baccini, M. and Matucci-Cerinic, M., 2014. A comparison of two podiatric protocols for metatarsalgia in patients with rheumatoid arthritis and osteoarthritis. *Clin Exp Rheumatol* 32(855), 63.

Bora, N.M., Molke, G.V. and Munot, H.R. 2015 Understanding human gait: A survey of traits for biometrics and biomedical applications, pp. 723-728, IEEE.

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

Bray, G.A., 2004. Medical consequences of obesity. *The Journal of Clinical Endocrinology & Metabolism* 89(6), 2583-2589.

Brenton-Rule, A., Bassett, S., Walsh, A. and Rome, K., 2011. The evaluation of walking footwear on postural stability in healthy older adults: an exploratory study. *Clinical Biomechanics* 26(8), 885-887.

Brenton-Rule, A., Mattock, J., Carroll, M., Dalbeth, N., Bassett, S., Menz, H.B. and Rome, K., 2012. Reliability of the TekScan MatScan® system for the measurement of postural stability in older people with rheumatoid arthritis. *Journal of foot and ankle research* 5(1), 21.

Bryant, A., Singer, K. and Tinley, P., 1999. Comparison of the reliability of plantar pressure measurements using the two-step and midgait methods of data collection. *Foot & ankle international* 20(10), 646-650.

Bryant, A.R., Tinley, P. and Singer, K.P., 2000. Normal values of plantar pressure measurements determined using the EMED-SF system. *Journal of the American Podiatric Medical Association* 90(6), 295-299.

Buldt, A.K., Allan, J.J., Landorf, K.B. and Menz, H.B., 2018. The relationship between foot posture and plantar pressure during walking in adults: a systematic review. *Gait & posture* 62, 56-67.

Buldt, A.K., Murley, G.S., Butterworth, P., Levinger, P., Menz, H.B. and Landorf, K.B., 2013. The relationship between foot posture and lower limb kinematics during walking: A systematic review. *Gait & posture* 38(3), 363-372.

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

Burnfield, M., 2010. Gait analysis: normal and pathological function. *Journal of Sports Science and Medicine* 9(2), 353.

Burns, J., Crosbie, J., Hunt, A. and Ouvrier, R., 2005. The effect of pes cavus on foot pain and plantar pressure. *Clinical Biomechanics* 20(9), 877-882.

Bus, S. and Waaijman, R., 2013. The value of reporting pressure–time integral data in addition to peak pressure data in studies on the diabetic foot: a systematic review. *Clinical Biomechanics* 28(2), 117-121.

Bus, S.A. and de Lange, A., 2005a. 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.

Bus, S.A., Maas, M., de Lange, A., Michels, R.P. and Levi, M., 2005b. Elevated plantar pressures in neuropathic diabetic patients with claw/hammer toe deformity. *Journal of biomechanics* 38(9), 1918-1925.

Bus, S.A., Ulbrecht, J.S. and Cavanagh, P.R., 2004. Pressure relief and load redistribution by custom-made insoles in diabetic patients with neuropathy and foot deformity. *Clinical Biomechanics* 19(6), 629-638.

Bus, S.A., Valk, G., Van Deursen, R., Armstrong, D.G., Caravaggi, C., Hlaváček, P., Bakker, K. and Cavanagh, P., 2008. The effectiveness of footwear and offloading interventions to prevent and heal foot ulcers and reduce plantar pressure in diabetes: a systematic review. *Diabetes/metabolism research and reviews* 24(S1), S162-S180.

Bus, S.A., Zwaferink, J.B., Dahmen, R. and Busch-Westbroek, T., 2020. State of the art design protocol for custom made footwear for people with diabetes and peripheral neuropathy. *Diabetes/Metabolism Research and Reviews* 36, e3237.

Butterworth, P.A., Landorf, K.B., Smith, S. and 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., Menz, H.B., Urquhart, D.M., Cicuttini, F.M., Landorf, K.B., Pasco, J.A., Brennan, S.L. and Wluka, A.E., 2016. Fat mass is associated with foot pain in men: the Geelong osteoporosis study. *The Journal of rheumatology* 43(1), 138-143.

Butterworth, P.A., Urquhart, D.M., Landorf, K.B., Wluka, A.E., Cicuttini, F.M. and 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.

Byun, S., Han, J.W., Kim, T.H. and Kim, K.W., 2016. Test-retest reliability and concurrent validity of a single tri-axial accelerometer-based gait analysis in older adults with normal cognition. *PLoS One* 11(7), e0158956.

Callisaya, M.L., Blizzard, L., Schmidt, M.D., Martin, K.L., McGinley, J.L., Sanders, L.M. and Srikanth, V.K., 2011. Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. *Age and ageing* 40(4), 481-487.

Callisaya, M.L., Blizzard, L., Schmidt, M.D., McGinley, J.L. and Srikanth, V.K., 2010. Ageing and gait variability—a population-based study of older people. *Age and ageing* 39(2), 191-197.

Campbell, A.J., Reinken, J., Allan, B. and Martinez, G., 1981. Falls in old age: a study of frequency and related clinical factors. *Age and ageing* 10(4), 264-270.

Carry, J. and Shepherd, R. 1998 Neurological rehabilitation: optimizing motor performance oxford butterworth, Heinemann Ltd.

Caselli, M.A. and George, D.H., 2003. Foot deformities: biomechanical and pathomechanical changes associated with aging, Part I. *Clinics in podiatric medicine and surgery* 20(3), 487-509, ix.

Castro, M., Abreu, S., Sousa, H., Machado, L., Santos, R. and Vilas-Boas, J.P., 2013. Ground reaction forces and plantar pressure distribution during occasional loaded gait. *Applied ergonomics* 44(3), 503-509.

Cavanagh, P.R., Hewitt Jr, F. and Perry, J., 1992. In-shoe plantar pressure measurement: a review. *The foot* 2(4), 185-194.

Cavanagh, P.R., Morag, E., Boulton, A., Young, M., Deffner, K. and Pammer, S., 1997. The relationship of static foot structure to dynamic foot function. *Journal of biomechanics* 30(3), 243-250.

Cesari, M., Kritchevsky, S.B., Penninx, B.W., Nicklas, B.J., Simonsick, E.M., Newman, A.B., Tylavsky, F.A., Brach, J.S., Satterfield, S. and Bauer, D.C., 2005. Prognostic value of usual gait speed in well-functioning older people—results from the Health, Aging and Body Composition Study. *Journal of the American Geriatrics Society* 53(10), 1675-1680.

Chaiwanichsiri, D., Janchai, S. and Tantisiriwat, N., 2009. Foot disorders and falls in older persons. *Gerontology* 55(3), 296-302.

Chamberlin, M.E., Fulwider, B.D., Sanders, S.L. and Medeiros, J.M., 2005. Does fear of falling influence spatial and temporal gait parameters in elderly persons beyond changes associated with normal aging? *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 60(9), 1163-1167.

Chang, B.-C., Liu, D.-H., Chang, J.L., Lee, S.-H. and Wang, J.-Y., 2014. Plantar pressure analysis of accommodative insole in older people with metatarsalgia. *Gait & posture* 39(1), 449-454.

Chatwin, K.E., Abbott, C.A., Boulton, A.J., Bowling, F.L. and Reeves, N.D., 2020. The role of foot pressure measurement in the prediction and prevention of diabetic foot ulceration—A comprehensive review. *Diabetes/Metabolism Research and Reviews* 36(4), e3258.

Chesnin, K.J., Selby-Silverstein, L. and Besser, M.P., 2000. Comparison of an in-shoe pressure measurement device to a force plate: concurrent validity of center of pressure measurements. *Gait & posture* 12(2), 128-133.

Cheung, J.T.-M. and Nigg, B.M., 2008a. Clinical applications of computational simulation of foot and ankle. *Sport-Orthopädie-Sport-Traumatologie-Sports Orthopaedics and Traumatology* 23(4), 264-271.

Cheung, J.T.-M. and Zhang, M., 2008b. Parametric design of pressure-relieving foot orthosis using statistics-based finite element method. *Medical engineering & physics* 30(3), 269-277.

Cheung, J.T.-M., Zhang, M., Leung, A.K.-L. and Fan, Y.-B., 2005. Three-dimensional finite element analysis of the foot during standing—a material sensitivity study. *Journal of biomechanics* 38(5), 1045-1054.

Chevalier, T.L., Hodgins, H. and Chockalingam, N., 2010. Plantar pressure measurements using an in-shoe system and a pressure platform: A comparison. *Gait & Posture* 31(3), 397-399.

Chiu, M.-C., Wu, H.-C., Chang, L.-Y. and Wu, M.-H., 2013. Center of pressure progression characteristics under the plantar region for elderly adults. *Gait & posture* 37(3), 408-412.

Chong, A., Al-Baghdadi, J. and Milburn, P., 2015. Human Plantar Pressure Image and Foot Shape Matching. *Journal of Biosciences and Medicines* 3(06), 36.

Chong, A.K., 2011. Low-cost compact cameras: A medical application in CMT disease monitoring. *The Photogrammetric Record* 26(134), 263-273.

Chong, A.K., 2012. Exploiting HD Camcorders for Close-Up Human Movement Applications. *The Photogrammetric Record* 27(138), 227-237.

Chong, A.K., Al-Baghdadi, J.A.A. and Milburn, P. 2014 Matching 3D plantar model with the force and pressure data of the loading phase of gait, pp. 704-708, IEEE.

Chong, A.K., Alshadli, D., AL-Baghdadi, J.A.A., Milburn, P. and Newsham-West, R. 2013 A video-based system for plantar surface acquisition during gait, pp. 1-4, National Taiwan Normal University.

Chong, A.K. and Mathieu, R., 2006. Near infrared photography for craniofacial anthropometric landmark measurement. *The Photogrammetric Record* 21(113), 16-28.

Chong, A.K., Milburn, P., Newsham-West, R. and Voert, M., 2009. High-accuracy photogrammetric technique for human spine measurement. *The Photogrammetric Record* 24(127), 264-279.

Chong, A.K., Milburn, P., West, R.N., ter Voert, M. and Croftc, H., 2008. Recent practical applications of close-range photogrammetry for complex motion study. *Int Arch Photogramm Rem Sens Spatial Inform Sci* 37(Part B5), 921-926.

Chung, M.-J. and Wang, M.-J., 2012. Gender and walking speed effects on plantar pressure distribution for adults aged 20–60 years. *Ergonomics* 55(2), 194-200.

Cimolin, V., Vismara, L., Galli, M., Zaina, F., Negrini, S. and Capodaglio, P., 2011. Effects of obesity and chronic low back pain on gait. *Journal of neuroengineering and rehabilitation* 8(1), 1.

Connell, B.R., Wolf, S.L. and Group, A.F., 1997. Environmental and behavioral circumstances associated with falls at home among healthy elderly individuals. *Archives of physical medicine and rehabilitation* 78(2), 179-186.

Control, C.f.D. and Prevention, 2006. Fatalities and injuries from falls among older adults---United States, 1993--2003 and 2001--2005. *MMWR: Morbidity and mortality weekly report* 55(45), 1221-1224.

Coudert, T., Vacher, P., Smits, C. and Van der Zande, M. 2006a A method to obtain 3D foot shape deformation during the gait cycle.

Coudert, T., Vacher, P., Smits, C. and Van der Zande, M. 2006b A method to obtain 3D foot shape deformation during the gait cycle, ISB.

Cousins, S.D., Morrison, S.C. and Drechsler, W.I., 2012. The reliability of plantar pressure assessment during barefoot level walking in children aged 7-11 years. *Journal of foot and ankle research* 5(1), 8.

Cowan, D.N., Jones, B.H. and Robinson, J.R., 1993. Foot morphologic characteristics and risk of exercise-related injury. *Archives of family medicine* 2(7), 773-777.

Cromwell, R.L. and Newton, R.A., 2004. Relationship between balance and gait stability in healthy older adults. *Journal of Aging and Physical Activity* 12(1), 90-100.

Crowe, A., Samson, M.M., Hoitsma, M.J. and van Ginkel, A.A., 1996. The influence of walking speed on parameters of gait symmetry determined from ground reaction forces. *Human Movement Science* 15(3), 347-367.

Cui, L., 2010. Analyzing the functional requirements of the sole of basketball shoes based on plantar pressure distribution. *J Shanxi Univ Sci Tech* 28, 311.

Cunha, F.V.M., Rodrigues, T.A.A., Alves, J.A., Santos, J.D.M. and Martins, M.d.C.C., 2016. Inter-relationship between foot prints and photogrammetry. *Manual Therapy, Posturology & Rehabilitation Journal* 14, 381.

Cunha, F.V.M., Rodrigues, T.A.A., Alves, J.A., Santos, J.D.M. and Martins, M.d.C.C., 2018. Inter-relationship between footprints and photogrammetry. *Manual Therapy, Posturology & Rehabilitation Journal* 14, 0-0.

D'Apuzzo, N., 2002. Surface measurement and tracking of human body parts from multi-image video sequences. *ISPRS journal of Photogrammetry and Remote Sensing* 56(5-6), 360-375.

D'Apuzzo, N. 2003 Human body motion capture from multi-image video sequences, pp. 54-61, International Society for Optics and Photonics.

D'arcangelo, P.R., Landorf, K.B., Munteanu, S.E., Zammit, G.V. and Menz, H.B., 2010. Radiographic correlates of hallux valgus severity in older people. *Journal of foot and ankle research* 3(1), 20.

Day, L. 2003 Falls in Older People: Risk Factors and Strategies for Prevention.: By SR Lord, C Sherrington, and HB Menz.(Pp 249; A $85.00.) Cambridge University Press (Private Bag 31, Port Melbourne, VIC 3207, Australia), 2001. ISBN 0-521-58964-9, BMJ Publishing Group Ltd.

de Castro, A.P., Rebelatto, J.R. and Aurichio, T.R., 2010. The relationship between foot pain, anthropometric variables and footwear among older people. *Applied ergonomics* 41(1), 93-97.

Deepashini, H., Omar, B., Paungmali, A., Amaramalar, N., Ohnmar, H. and Leonard, J., 2014. An insight into the plantar pressure distribution of the foot in clinical practice: Narrative review. *Polish Annals of medicine* 21(1), 51-56.

Demirbüken, İ., Özgül, B., Timurtaş, E., Yurdalan, S.U., Çekin, M.D. and Polat, M.G., 2019. Gender and age impact on plantar pressure distribution in early adolescence. *Acta orthopaedica et traumatologica turcica* 53(3), 215-220.

Derawi, M.O., Bours, P. and Holien, K. 2010 Improved cycle detection for accelerometer based gait authentication, pp. 312-317, IEEE.

Di Stasi, S.L., Logerstedt, D., Gardinier, E.S. and 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.

Dimitrijevic, M. and Larsson, L.-E., 1981. Neural control of gait: clinical neurophysiological aspects. *Stereotactic and Functional Neurosurgery* 44(1-3), 152-159.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P. and Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *J. Biomech. Eng.* 123(1), 27-32.

Dowling, A., Steele, J. and Baur, L., 2001. Does obesity influence foot structure and plantar pressure patterns in prepubescent children? *International journal of obesity* 25(6), 845-852.

Duckworth, T., Boulton, A., Betts, R., Franks, C. and Ward, J., 1985. Plantar pressure measurements and the prevention of ulceration in the diabetic foot. *The Journal of bone and joint surgery. British volume* 67(1), 79-85.

Dufour, A.B., Losina, E., Menz, H.B., LaValley, M.P. and Hannan, M.T., 2017. Obesity, foot pain and foot disorders in older men and women. *Obesity research & clinical practice* 11(4), 445-453.

Dunn, J., Link, C., Felson, D., Crincoli, M., Keysor, J. and McKinlay, J., 2004. Prevalence of foot and ankle conditions in a multiethnic community sample of older adults. *American journal of epidemiology* 159(5), 491-498.

Elble, R., Thomas, S.S., Higgins, C. and Colliver, J., 1991. Stride-dependent changes in gait of older people. *Journal of neurology* 238(1), 1-5.

Ellington, J.K., 2011. Hammertoes and clawtoes: proximal interphalangeal joint correction. *Foot Ankle Clin* 16(4), 547-558.

Erdemir, A., Saucerman, J.J., Lemmon, D., Loppnow, B., Turso, B., Ulbrecht, J.S. and Cavanagh, P.R., 2005. Local plantar pressure relief in therapeutic footwear: design guidelines from finite element models. *Journal of biomechanics* 38(9), 1798-1806.

Fawzy, O.A., Arafa, A.I., Wakeel, M.A.E. and Kareem, S.H.A., 2014. Plantar pressure as a risk assessment tool for diabetic foot ulceration in Egyptian patients with diabetes. *Clinical Medicine Insights: Endocrinology and Diabetes* 7, CMED. S17088.

Federer, A.E., Tainter, D.M., Adams, S.B. and Schweitzer, K.M., 2018. Conservative management of metatarsalgia and lesser toe deformities. *Foot and ankle clinics* 23(1), 9-20.

Feng, Q. (2015) Dynamic foot model, Institute of Textiles and Clothing, The Hong Kong Polytechnic University.

Ferraro, R.A., Pinto-Zipp, G., Simpkins, S. and Clark, M., 2013. Effects of an inclined walking surface and balance abilities on spatiotemporal gait parameters of older adults. *Journal of geriatric physical therapy* 36(1), 31-38.

Forghany, S., Bonanno, D.R., Menz, H.B. and Landorf, K.B., 2018. An anatomically-based masking protocol for the assessment of in-shoe plantar pressure measurement of the forefoot. *Journal of foot and ankle research* 11(1), 31.

Fourchet, F., Maffiuletti, N.A., Agosti, F., Patrizi, A. and Sartorio, A., 2020. Impact of rocker sole footwear on plantar pressure distribution during standing and walking in adult obese women. *Disability and rehabilitation* 42(7), 927-930.

Franco, P.S., Moro, C.F., Figueiredo, M.M., Azevedo, R.R., Ceccon, F.G. and Carpes, F.P., 2018. Within and between-days repeatability and variability of plantar pressure measurement during walking in children, adults and older adults. *Advances in Rheumatology* 58(1), 15.

Franz, J.R. and Kram, R., 2013. Advanced age affects the individual leg mechanics of level, uphill, and downhill walking. *Journal of biomechanics* 46(3), 535-540.

Franz, J.R. and Kram, R., 2014. Advanced age and the mechanics of uphill walking: a joint-level, inverse dynamic analysis. *Gait & posture* 39(1), 135-140.

Fraser, C.S. and Al-Ajlouni, S., 2006. Zoom-dependent camera calibration in digital close-range photogrammetry. *Photogrammetric Engineering & Remote Sensing* 72(9), 1017-1026.

Frey, C., 2000. Foot health and shoewear for women. *Clinical Orthopaedics and Related Research (1976-2007)* 372, 32-44.

Fritz, B., Schmeltzpfenning, T., Plank, C., Hein, T. and Grau, S., 2013. Anthropometric influences on dynamic foot shape: Measurements of plantar three-dimensional foot deformation. *Footwear Science* 5(2), 121-129.

Fryer, J., Mitchell, H. and Chandler, J.H. (2007) Applications of 3D measurement from images, Whittles Publishing.

Frykberg, R.G., Lavery, L.A., Pham, H., Harvey, C., Harkless, L. and Veves, A., 1998. Role of neuropathy and high foot pressures in diabetic foot ulceration. *Diabetes care* 21(10), 1714-1719.

Fuchioka, S., Iwata, A., Higuchi, Y., Miyake, M., Kanda, S. and Nishiyama, T., 2015. The forward velocity of the center of pressure in the midfoot is a major predictor of gait speed in older Adults. *International Journal of Gerontology* 9(2), 119-122.

Gabell, A. and Nayak, U., 1984. The effect of age on variability in gait. *Journal of gerontology* 39(6), 662-666.

Gabell, A., Simons, M. and Nayak, U., 1985. Falls in the healthy elderly: predisposing causes. *Ergonomics* 28(7), 965-975.

Galantucci, L., Lavecchia, F. and Percoco, G., 2010. A simple photogrammetric system for automatic capture and measurement of facial soft tissues during movement. *Innovative Development in Design and Manufacturing. London: Taylor & Francis Group*, 151-156.

Galantucci, L.M., Percoco, G. and Lavecchia, F., 2013. A new three-dimensional photogrammetric face scanner for the morpho-biometric 3D feature extraction applied to a massive field analysis of Italian attractive women. *Procedia CIRP* 5, 259-264.

Gallentine, J.W. and DeOrio, J.K., 2005. Removal of the second toe for severe hammertoe deformity in elderly patients. *Foot & ankle international* 26(5), 353-358.

Gefen, A., 2003. Plantar soft tissue loading under the medial metatarsals in the standing diabetic foot. *Medical engineering & physics* 25(6), 491-499.

Gerber, H., 1982. A system for measuring dynamic pressure distribution under the human foot. *Journal of Biomechanics* 15(3), 225-227.

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

Gimunova, M., Zvonař, M. and Mikeska, O., 2018. The effect of aging and gender on plantar pressure distribution during the gait in elderly. *Acta of bioengineering and biomechanics* 20(3).

Gnanasundaram, S., Ramalingam, P., Das, B.N. and Viswanathan, V., 2020. Gait changes in persons with diabetes: Early risk marker for diabetic foot ulcer. *Foot and Ankle Surgery* 26(2), 163-168.

Gorter, K.J., Kuyvenhoven, M.M. and de Melker, R.A., 2000. Nontraumatic foot complaints in older people. A population-based survey of risk factors, mobility, and well-being. *Journal of the American Podiatric Medical Association* 90(8), 397-402.

Gottschall, J.S., Okorokov, D.Y., Okita, N. and Stern, K.A., 2011. Walking strategies during the transition between level and hill surfaces. *Journal of applied biomechanics* 27(4), 355-361.

GR Neri, S., S Oliveira, J., B Dario, A., M Lima, R. and Tiedemann, A., 2020. Does obesity increase the risk and severity of falls in people aged 60 years and older? A systematic review and meta-analysis of observational studies. *The Journals of Gerontology: Series A* 75(5), 952-960.

Grabiner, P.C., Biswas, S.T. and Grabiner, M.D., 2001. Age-related changes in spatial and temporal gait variables. *Archives of physical medicine and rehabilitation* 82(1), 31-35.

Grampp, J., Willson, J. and Kernozek, T., 2000. The plantar loading variations to uphill and downhill gradients during treadmill walking. *Foot & Ankle International* 21(3), 227-231.

Grenness, M.J., Osborn, J.E. and Tyas, M.J., 2008. Mapping tooth surface loss with a fixed-base stereo camera. *The Photogrammetric Record* 23(122), 194-207.

Grundy, M., Tosh, P., McLeish, R. and Smidt, L., 1975. An investigation of the centres of pressure under the foot while walking. *Bone & Joint Journal* 57(1), 98-103.

Gu, Y., Ren, X., Li, J., Lake, M., Zhang, Q. and Zeng, Y., 2010. Computer simulation of stress distribution in the metatarsals at different inversion landing angles using the finite element method. *International orthopaedics* 34(5), 669-676.

Guedes, R.C., Dias, R.C., Pereira, L.S., Silva, S.L., Lustosa, L.P. and Dias, J., 2014. Influence of dual task and frailty on gait parameters of older community-dwelling individuals. *Brazilian journal of physical therapy* 18(5), 445-452.

Guo, L.-Y., Su, F.-C., Yang, C.-H., Wang, S.-H., Chang, J.-J., Wu, W.-L. and Lin, H.-T., 2006. Effects of speed and incline on lower extremity kinematics during treadmill jogging in healthy subjects. *Biomedical Engineering: Applications, Basis and Communications* 18(02), 73-79.

Hackney, J.M., Hunt, G.C., Lerche, F.F., Voi, P. and Smith, J.W., 2010. An external shoe modification for reducing metatarsal head pressure in people with metatarsalgia. *JPO: Journal of Prosthetics and Orthotics* 22(1), 37-42.

Hafer, J.F., Lenhoff, M.W., Song, J., Jordan, J.M., Hannan, M.T. and Hillstrom, H.J., 2013. Reliability of plantar pressure platforms. *Gait & posture* 38(3), 544-548.

Hajek, A., Brettschneider, C., van der Leeden, C., Lühmann, D., Oey, A., Wiese, B., Weyerer, S., Werle, J., Fuchs, A. and Pentzek, M., 2020. Prevalence and factors associated with obesity among the oldest old. *Archives of Gerontology and Geriatrics*, 104069.

Hallemans, A., De Clercq, D., Van Dongen, S. and Aerts, P., 2006. Changes in foot-function parameters during the first 5 months after the onset of independent walking: a longitudinal follow-up study. *Gait & posture* 23(2), 142-148.

Hamacher, D., Singh, N., Van Dieen, J., Heller, M. and Taylor, W., 2011. Kinematic measures for assessing gait stability in elderly individuals: a systematic review. *Journal of The Royal Society Interface* 8(65), 1682-1698.

Hamada, H.A., Mosaad, D., Fahim, M., Abd El-Samea, G., Youssef, A. and Gouda Matar, A., 2019. Dynamic plantar pressure and ground reaction force during pregnancy: A prospective longitudinal study. *Cogent Engineering* 6(1), 1602969.

Han, J. and Bhanu, B., 2005. Individual recognition using gait energy image. *IEEE transactions on pattern analysis and machine intelligence* 28(2), 316-322.

Han, T.R., Paik, N.J. and Im, M.S., 1999. Quantification of the path of center of pressure (COP) using an F-scan in-shoe transducer. *Gait & posture* 10(3), 248-254.

Hannan, M.T., Menz, H.B., Jordan, J.M., Cupples, L.A., Cheng, C.-H. and Hsu, Y.-H., 2013. Hallux valgus and lesser toe deformities are highly heritable in adult men and women: the Framingham foot study. *Arthritis care & research* 65(9), 1515.

Härdi, I., Bridenbaugh, S.A., Gschwind, Y.J. and Kressig, R.W., 2014. The effect of three different types of walking aids on spatio-temporal gait parameters in community-dwelling older adults. *Aging clinical and experimental research* 26(2), 221-228.

Hartmann, A., Luzi, S., Murer, K., de Bie, R.A. and de Bruin, E.D., 2009a. Concurrent validity of a trunk tri-axial accelerometer system for gait analysis in older adults. *Gait & posture* 29(3), 444-448.

Hartmann, A., Murer, K., de Bie, R.A. and de Bruin, E.D., 2009b. Reproducibility of spatio-temporal gait parameters under different conditions in older adults using a trunk tri-axial accelerometer system. *Gait & posture* 30(3), 351-355.

Hausdorff, J.M., Cudkowicz, M.E., Firtion, R., Wei, J.Y. and Goldberger, A.L., 1998. Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntington's disease. *Movement disorders* 13(3), 428-437.

Hausdorff, J.M., Rios, D.A. and Edelberg, H.K., 2001. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Archives of physical medicine and rehabilitation* 82(8), 1050-1056.

Hennig, E.M., Staats, A. and Rosenbaum, D., 1994. Plantar pressure distribution patterns of young school children in comparison to adults. *Foot & ankle international* 15(1), 35-40.

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

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

Hida, T., Okuda, R., Yasuda, T., Jotoku, T., Shima, H. and Neo, M., 2017. Comparison of plantar pressure distribution in patients with hallux valgus and healthy matched controls. *Journal of Orthopaedic Science* 22(6), 1054-1059.

Hill, C.L., Gill, T.K., Menz, H.B. and Taylor, A.W., 2008. Prevalence and correlates of foot pain in a population-based study: the North West Adelaide health study. *Journal of foot and ankle research* 1(1), 2.

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

Hills, A., Hennig, E., McDonald, M. and Bar-Or, O., 2001b. Plantar pressure differences between obese and non-obese adults: a biomechanical analysis. *International journal of obesity* 25(11), 1674-1679.

Hillstrom, H.J., Song, J., Kraszewski, A.P., Hafer, J.F., Mootanah, R., Dufour, A.B., Chow, B.S. and Deland III, J.T., 2013. Foot type biomechanics part 1: structure and function of the asymptomatic foot. *Gait & posture* 37(3), 445-451.

Ho, I.-J., Hou, Y.-Y., Yang, C.-H., Wu, W.-L., Chen, S.-K. and Guo, L.-Y., 2010. Comparison of plantar pressure distribution between different speed and incline during treadmill jogging. *Journal of sports science & medicine* 9(1), 154.

Hodge, M.C., Bach, T.M. and Carter, G.M., 1999. Orthotic management of plantar pressure and pain in rheumatoid arthritis. *Clinical biomechanics* 14(8), 567-575.

Hollman, J.H., McDade, E.M. and Petersen, R.C., 2011. Normative spatiotemporal gait parameters in older adults. *Gait & posture* 34(1), 111-118.

Honeycutt, P.H. and Ramsey, P., 2002. Factors contributing to falls in elderly men living in the community. *Geriatric nursing* 23(5), 250-257.

Hong, S.-W., Leu, T.-H., Li, J.-D., Wang, T.-M., Ho, W.-P. and Lu, T.-W., 2014. Influence of inclination angles on intra-and inter-limb load-sharing during uphill walking. *Gait & posture* 39(1), 29-34.

Hong, S.-W., Leu, T.-H., Wang, T.-M., Li, J.-D., Ho, W.-P. and Lu, T.-W., 2015. Control of body's center of mass motion relative to center of pressure during uphill walking in the elderly. *Gait & posture* 42(4), 523-528.

Horisberger, M., Hintermann, B. and Valderrabano, V., 2009. Alterations of plantar pressure distribution in posttraumatic end-stage ankle osteoarthritis. *Clinical Biomechanics* 24(3), 303-307.

Houck, J.R., Tome, J.M. and Nawoczenski, D.A., 2008. Subtalar neutral position as an offset for a kinematic model of the foot during walking. *Gait & posture* 28(1), 29-37.

Hsiao, H., Guan, J. and Weatherly, M., 2002. Accuracy and precision of two in-shoe pressure measurement systems. *Ergonomics* 45(8), 537-555.

Hsu, C.-C., Tsai, W.-C., Chen, C.P.-C., Shau, Y.-W., Wang, C.-L., Chen, M.J.-L. and Chang, K.-J., 2005. Effects of aging on the plantar soft tissue properties under the metatarsal heads at different impact velocities. *Ultrasound in medicine & biology* 31(10), 1423-1429.

Hughes, J., 1993. The clinical use of pedobarography. *Acta Orthopaedica Belgica* 59, 10-10.

Hughes, J., Pratt, L., Linge, K., Clark, P. and Klenerman, L., 1991. Reliability of pressure measurements: the EM ED F system. *Clinical Biomechanics* 6(1), 14-18.

Hurkmans, H., Bussmann, J., Benda, E., Verhaar, J. and Stam, H., 2003. Techniques for measuring weight bearing during standing and walking. *Clinical Biomechanics* 18(7), 576-589.

Hurkmans, H., Bussmann, J., Benda, E., Verhaar, J. and Stam, H., 2006. Accuracy and repeatability of the Pedar Mobile system in long-term vertical force measurements. *Gait & Posture* 23(1), 118-125.

Huxham, F.E., Goldie, P.A. and Patla, A.E., 2001. Theoretical considerations in balance assessment. *Australian Journal of Physiotherapy* 47(2), 89-101.

Item-Glatthorn, J.F., Casartelli, N.C. and Maffiuletti, N.A., 2016. Reproducibility of gait parameters at different surface inclinations and speeds using an instrumented treadmill system. *Gait & posture* 44, 259-264.

Janeh, O., Langbehn, E., Steinicke, F., Bruder, G., Gulberti, A. and Poetter-Nerger, M., 2017. Walking in virtual reality: Effects of manipulated visual self-motion on walking biomechanics. *ACM Transactions on Applied Perception (TAP)* 14(2), 1-15.

Jannink, M., van Dijk, H., Ijzerman, M., Groothuis-Oudshoorn, K., Groothoff, J. and Lankhurst, G., 2006. Effectiveness of custom-made orthopaedic shoes in the reduction of foot pain and pressure in patients with degenerative disorders of the foot. *Foot & ankle international* 27(11), 974-979.

Janssen, I. and Mark, A.E., 2007. Elevated body mass index and mortality risk in the elderly. *Obesity reviews* 8(1), 41-59.

Jellema, A.H., Huysmans, T., Hartholt, K. and van der Cammen, T.J., 2019. Shoe design for older adults: Evidence from a systematic review on the elements of optimal footwear. *Maturitas* 127, 64-81.

Jensen, R.R., Paulsen, R.R. and Larsen, R. 2009a Analysis of gait using a treadmill and a time-of-flight camera, pp. 154-166, Springer.

Jensen, R.R., Paulsen, R.R. and Larsen, R. 2009b Analyzing gait using a time-of-flight camera, pp. 21-30, Springer.

Jezersek, M., Novak, B. and Mozina, J., 2011. Three-dimensional laser based measurement of human foot during walking. *Footwear Science* 3(sup1), S81-S83.

Jonely, H., Brismée, J.-M., Sizer Jr, P.S. and James, C.R., 2011. Relationships between clinical measures of static foot posture and plantar pressure during static standing and walking. *Clinical Biomechanics* 26(8), 873-879.

Kanatli, U., Yetkin, H., Simsek, A., Ozturk, A.M., Esen, E. and Besli, K., 2008. Pressure distribution patterns under the metatarsal heads in healthy individuals. *Acta Orthop Traumatol Turc* 42(1), 26-30.

Kandil, O.D., Aboelazm, S.N. and Mabrouk, M.S., 2014. Foot biometrics: gender differences in plantar pressure distribution in standing position. *Am J Biomed Eng* 4(1), 1-9.

Kang, H.G. and Dingwell, J.B., 2008a. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. *Journal of biomechanics* 41(14), 2899-2905.

Kang, H.G. and Dingwell, J.B., 2008b. Separating the effects of age and walking speed on gait variability. *Gait & posture* 27(4), 572-577.

Kang, J.-H., Chen, M.-D., Chen, S.-C. and Hsi, W.-L., 2006. Correlations between subjective treatment responses and plantar pressure parameters of metatarsal pad treatment in metatarsalgia patients: a prospective study. *BMC musculoskeletal disorders* 7(1), 95.

Kästenbauer, T., Sokol, G. and Irsigler, K., 1995. The effects of walking uphill or downhill on dynamic plantar foot pressure in diabetic patients. *The Foot* 5(4), 199-201.

Kavlak, Y., 2015. The Relation of Hallux Valgus Severity With Foot Function and Balance in Older Men. *Fizyoterapi Rehabilitasyon* 26(2), 93-99.

Kawamura, K., Tokuhiro, A. and Takechi, H., 1991. Gait analysis of slope walking: a study on step length, stride width, time factors and deviation in the center of pressure. *Acta Medica Okayama* 45(3), 179-184.

Kazhdan, M., Bolitho, M. and Hoppe, H. 2006 Poisson surface reconstruction.

Keijsers, N., Stolwijk, N., Louwerens, J. and Duysens, J., 2013. Classification of forefoot pain based on plantar pressure measurements. *Clinical biomechanics* 28(3), 350-356.

Kellis, E., 2001. Plantar pressure distribution during barefoot standing, walking and landing in preschool boys. *Gait & posture* 14(2), 92-97.

Kernozek, T. and LaMott, E., 1995. Comparisons of plantar pressures between the elderly and young adults. *Gait & posture* 3(3), 143-148.

Kernozek, T., LaMott, E. and Dancisak, M., 1996. Reliability of an in-shoe pressure measurement system during treadmill walking. *Foot & Ankle International* 17(4), 204-209.

Kim, J.-a., Lim, O.-b. and Yi, C.-h., 2013a. Plantar Pressure Distribution During Level Walking, and Stair Ascent and Descent in Asymptomatic Flexible Flatfoot. *Physical Therapy Korea* 20(4), 55-64.

Kim, J., Kim, K. and Gubler, C., 2013b. Comparisons of plantar pressure distributions between the dominant and non-dominant sides of older women during walking. *Journal of Physical Therapy Science* 25(3), 313-315.

Kimel-Naor, S., Gottlieb, A. and Plotnik, M., 2017. The effect of uphill and downhill walking on gait parameters: A self-paced treadmill study. *Journal of biomechanics* 60, 142-149.

Kimmeskamp, S. and Hennig, E.M., 2001. Heel to toe motion characteristics in Parkinson patients during free walking. *Clinical biomechanics* 16(9), 806-812.

Kimura, M., Mochimaru, M. and Kanade, T. 2008 Measurement of 3D foot shape deformation in motion, pp. 1-8.

Kimura, M., Mochimaru, M. and Kanade, T., 2011. 3D measurement of feature cross-sections of foot while walking. *Machine Vision and Applications* 22(2), 377-388.

Kimura, M., Mochimaru, M., Kouchi, M. and Kanade, T. 2005 3D cross-sectional shape measurement of the foot while walking, pp. 34-35.

Klammer, G. and Espinosa, N., 2019. Scientific Evidence in the Treatment of Metatarsalgia. *Foot and ankle clinics* 24(4), 585-598.

Ko, M., Hughes, L. and Lewis, H., 2012. Walking speed and peak plantar pressure distribution during barefoot walking in persons with diabetes. *Physiotherapy Research International* 17(1), 29-35.

Kolahi, A., Hoviattalab, M., Rezaeian, T., Alizadeh, M., Bostan, M. and Mokhtarzadeh, H., 2007. Design of a marker-based human motion tracking system. *Biomedical Signal Processing and Control* 2(1), 59-67.

Koller, U., Willegger, M., Windhager, R., Wanivenhaus, A., Trnka, H.J. and Schuh, R., 2014. Plantar pressure characteristics in hallux valgus feet. *Journal of Orthopaedic Research* 32(12), 1688-1693.

Kouchi, M., Kimura, M. and Mochimaru, M., 2009. Deformation of foot cross-section shapes during walking. *Gait & posture* 30(4), 482-486.

Krauss, I., Valiant, G., Horstmann, T. and Grau, S., 2010. Comparison of female foot morphology and last design in athletic footwear—Are men's lasts appropriate for women? *Research in Sports Medicine* 18(2), 140-156.

Kressig, R.W. and Beauchet, O., 2006. Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging clinical and experimental research* 18(2), 174-176.

Kressig, R.W., Gregor, R.J., Oliver, A., Waddell, D., Smith, W., O'Grady, M., Curns, A.T., Kutner, M. and Wolf, S.L., 2004. Temporal and spatial features of gait in older adults transitioning to frailty. *Gait & posture* 20(1), 30-35.

Kwan, R.L.-C., Zheng, Y.-P. and Cheing, G.L.-Y., 2010. The effect of aging on the biomechanical properties of plantar soft tissues. *Clinical Biomechanics* 25(6), 601-605.

Lam, W.-K., Liu, H., Wu, G.-Q., Liu, Z.-L. and Sun, W., 2019a. Effect of shoe wearing time and midsole hardness on ground reaction forces, ankle stability and perceived comfort in basketball landing. *Journal of Sports Sciences* 37(20), 2347-2355.

Lam, W.-K., Ng, W.X. and Kong, P.W., 2017. Influence of shoe midsole hardness on plantar pressure distribution in four basketball-related movements. *Research in Sports Medicine* 25(1), 37-47.

Lam, W.K., Kan, W.H., Chia, J.S. and Kong, P.W., 2019b. Effect of shoe modifications on biomechanical changes in basketball: A systematic review. *Sports Biomechanics*, 1-27.

Lamoth, C.J., van Deudekom, F.J., van Campen, J.P., Appels, B.A., de Vries, O.J. and Pijnappels, M., 2011. Gait stability and variability measures show effects of impaired cognition and dual tasking in frail people. *Journal of neuroengineering and rehabilitation* 8(1), 2.

Lane, T.J., Landorf, K.B., Bonanno, D.R., Raspovic, A. and Menz, H.B., 2014. Effects of shoe sole hardness on plantar pressure and comfort in older people with forefoot pain. *Gait & Posture* 39(1), 247-251.

Lay, A.N., Hass, C.J. and Gregor, R.J., 2006. The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of biomechanics* 39(9), 1621-1628.

Ledoux, W.R., Shofer, J.B., Cowley, M.S., Ahroni, J.H., Cohen, V. and Boyko, E.J., 2013. Diabetic foot ulcer incidence in relation to plantar pressure magnitude and measurement location. *Journal of Diabetes and its Complications* 27(6), 621-626.

Lee, H., Sullivan, S.J. and Schneiders, A.G., 2013a. The use of the dual-task paradigm in detecting gait performance deficits following a sports-related concussion: a systematic review and meta-analysis. *Journal of science and Medicine in Sport* 16(1), 2-7.

Lee, I.-h. and Park, S.-y., 2013b. A comparison of gait characteristics in the elderly people, people with knee pain, and people who are walker dependent people. *Journal of physical therapy science* 25(8), 973-976.

Lee, P.Y., Landorf, K.B., Bonanno, D.R. and Menz, H.B., 2014a. Comparison of the pressure-relieving properties of various types of forefoot pads in older people with forefoot pain. *Journal of foot and ankle research* 7(1), 18.

Lee, S.J. and Hidler, J., 2008. Biomechanics of overground vs. treadmill walking in healthy individuals. *Journal of applied physiology* 104(3), 747-755.

Lee, Y.-C., Lin, G. and Wang, M.-J.J., 2014b. Comparing 3D foot scanning with conventional measurement methods. *Journal of foot and ankle research* 7(1), 44.

Lefloch, D., Nair, R., Lenzen, F., Schäfer, H., Streeter, L., Cree, M.J., Koch, R. and Kolb, A. (2013) Time-of-Flight and Depth Imaging. Sensors, Algorithms, and Applications, pp. 3-24, Springer.

Leroux, A., Fung, J. and Barbeau, H., 2002. Postural adaptation to walking on inclined surfaces: I. Normal strategies. *Gait & posture* 15(1), 64-74.

Levangie, P.K. and Norkin, C.C., 2000. Joint Structure and Function; A Comprehensive Analysis. 3rd. *Philadelphia: FA. Davis Company*.

Leveille, S.G., Guralnik, J.M., Ferrucci, L., Hirsch, R., Simonsick, E. and Hochberg, M.C., 1998. Foot pain and disability in older women. *American journal of epidemiology* 148(7), 657-665.

Liu, S., Cui, Y., Sanchez, S. and Stricker, D., 2011. Foot scanning and deformation estimation using time-of-flight cameras. *Footwear Science* 3(sup1), S98-S99.

Lizama, L.E.C., Pijnappels, M., Rispens, S.M., Reeves, N.P., Verschueren, S.M. and van Dieën, J.H., 2015. Mediolateral balance and gait stability in older adults. *Gait & Posture* 42(1), 79-84.

López, D.L., González, L.C., Iglesias, M.E.L., Canosa, J.L.S., Sanz, D.R., Lobo, C.C. and de Bengoa Vallejo, R.B., 2016. Quality of life impact related to foot health in a sample of older people with hallux valgus. *Aging and disease* 7(1), 45.

Lord, M., 1981. Foot pressure measurement: a review of methodology. *Journal of biomedical engineering* 3(2), 91-99.

Lord, S., Sherrington, C., Menz, H. and Close, J., 2007a. Falls in older people: risk factors and strategies for prevention. *Falls in older people: risk factors and strategies for prevention.* (Ed. 2).

Lord, S.R., Sherrington, C., Menz, H.B. and Close, J.C. (2007b) Falls in older people: risk factors and strategies for prevention, Cambridge University Press.

Lord, S.R., Ward, J.A., Williams, P. and Anstey, K.J., 1993. An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. *Australian journal of public health* 17(3), 240-245.

Losito, J.M. (2017) Athletic Footwear and Orthoses in Sports Medicine, pp. 381-387, Springer.

Luhmann, T., 2010. Close range photogrammetry for industrial applications. *ISPRS journal of photogrammetry and remote sensing* 65(6), 558-569.

Luhmann, T., Robson, S., Kyle, S. and Harley, I., 2006. Close range photogrammetry. *Whittles, Caithness*.

Lundeen, S., Lundquist, K., Cornwall, M.W. and McPoil, T.G., 1994. Plantar pressures during level walking compared with other ambulatory activities. *Foot & ankle international* 15(6), 324-328.

Machado, Á.S., Bombach, G.D., Duysens, J. and Carpes, F.P., 2016. Differences in foot sensitivity and plantar pressure between young adults and elderly. *Archives of gerontology and geriatrics* 63, 67-71.

MacWilliams, B. and Armstrong, P. 2000 Clinical applications of plantar pressure measurement in pediatric orthopedics, pp. 143-150, IEEE.

Majid, Z., Chong, A.K., Ahmad, A., Setan, H. and Samsudin, A.R., 2005. Photogrammetry and 3D laser scanning as spatial data capture techniques for a national craniofacial database. *The Photogrammetric Record* 20(109), 48-68.

Majid, Z., Setan, H. and Chong, A., 2008. Integration of stereophotogrammetry and triangulation-based laser scanning system for precise mapping of craniofacial morphology. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 37.

Maki, B.E., 1997. Gait changes in older adults: predictors of falls or indicators of fear? *Journal of the American geriatrics society* 45(3), 313-320.

Maki, B.E. and McIlroy, W.E., 2006. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age and ageing* 35(suppl_2), ii12-ii18.

Maluf, K.S., Morley Jr, R.E., Richter, E.J., Klaesner, J.W. and Mueller, M.J., 2004. Foot pressures during level walking are strongly associated with pressures during other ambulatory activities in subjects with diabetic neuropathy. *Archives of physical medicine and rehabilitation* 85(2), 253-260.

Mao, D., Li, J. and Hong, Y., 2006. The duration and plantar pressure distribution during one-leg stance in Tai Chi exercise. *Clinical biomechanics* 21(6), 640-645.

Marigold, D.S. and Patla, A.E., 2008. Age-related changes in gait for multi-surface terrain. *Gait & posture* 27(4), 689-696.

Martedi, S., Saito, H. and Servieres, M. 2009 Shape Measurement System of Foot Sole Surface from Flatbed Scanner Image, pp. 338-341, Citeseer.

Martin, K.L., Blizzard, L., Wood, A.G., Srikanth, V., Thomson, R., Sanders, L.M. and Callisaya, M.L., 2013. Cognitive function, gait, and gait variability in older people: a population-based study. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 68(6), 726-732.

Martínez-Martí, F., Ocón-Hernández, O., Martínez-García, M.S., Torres-Ruiz, F., Martínez-Olmos, A., Carvajal, M.A., Banqueri, J. and Palma, A.J., 2019. Plantar pressure changes and their relationships with low back pain during pregnancy using instrumented insoles. *Journal of Sensors* 2019.

Martinez-Nova, A., Huerta, J.P. and Sanchez-Rodriguez, R., 2008. Cadence, age, and weight as determinants of forefoot plantar pressures using the Biofoot in-shoe system. *Journal of the American Podiatric Medical Association* 98(4), 302-310.

Martínez-Nova, A., Sánchez-Rodríguez, R., Pérez-Soriano, P., Llana-Belloch, S., Leal-Muro, A. and Pedrera-Zamorano, J.D., 2010. Plantar pressures determinants in mild Hallux Valgus. *Gait & posture* 32(3), 425-427.

Mattar, R., Diab, J., Wehbe, S., Merhej, C. and Abu-Faraj, Z.O. 2015 Normative plantar pressure distribution in asymptomatic adult subjects: A pilot study, pp. 222-225, IEEE.

McFadyen, B.J. and Winter, D.A., 1988. An integrated biomechanical analysis of normal stair ascent and descent. *Journal of biomechanics* 21(9), 733-744.

McIntosh, A.S., Beatty, K.T., Dwan, L.N. and Vickers, D.R., 2006. Gait dynamics on an inclined walkway. *Journal of biomechanics* 39(13), 2491-2502.

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

McPoil Jr, T.G., 1988. Footwear. *Physical therapy* 68(12), 1857-1865.

McPoil, T.G., Cornwall, M.W., Dupuis, L. and Cornwell, M., 1999. Variability of plantar pressure data. A comparison of the two-step and midgait methods. *Journal of the American Podiatric Medical Association* 89(10), 495-501.

Mei, Q., Fernandez, J., Fu, W., Feng, N. and Gu, Y., 2015. A comparative biomechanical analysis of habitually unshod and shod runners based on a foot morphological difference. *Human movement science* 42, 38-53.

Melai, T., IJzerman, T.H., Schaper, N.C., de Lange, T.L., Willems, P.J., Meijer, K., Lieverse, A.G. and Savelberg, H.H., 2011. Calculation of plantar pressure time integral, an alternative approach. *Gait & posture* 34(3), 379-383.

Melzer, I. and Oddsson, L.I., 2016. Altered characteristics of balance control in obese older adults. *Obesity research & clinical practice* 10(2), 151-158.

Menant, J.C., Steele, J.R., Menz, H.B., Munro, B.J. and Lord, S.R., 2008. Optimizing footwear for older people at risk of falls.

Menant, J.C., Steele, J.R., Menz, H.B., Munro, B.J. and Lord, S.R., 2009a. Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. *Gait & posture* 29(3), 392-397.

Menant, J.C., Steele, J.R., Menz, H.B., Munro, B.J. and Lord, S.R., 2009b. Rapid gait termination: effects of age, walking surfaces and footwear characteristics. *Gait & posture* 30(1), 65-70.

Mensink, G., Schienkiewitz, A., Haftenberger, M., Lampert, T., Ziese, T. and Scheidt-Nave, C., 2013. Overweight and obesity in Germany.

Menz, H.B. (2008) Foot problems in older people: assessment and management, Elsevier Health Sciences.

Menz, H.B., 2015. Biomechanics of the ageing foot and ankle: a mini-review. *Gerontology* 61(4), 381-388.

Menz, H.B., 2016. Chronic foot pain in older people. *Maturitas* 91, 110-114.

Menz, H.B., Auhl, M. and Spink, M.J., 2018. Foot problems as a risk factor for falls in community-dwelling older people: a systematic review and meta-analysis. *Maturitas* 118, 7-14.

Menz, H.B., Barr, E.L. and Brown, W.J., 2011. Predictors and persistence of foot problems in women aged 70 years and over: a prospective study. *Maturitas* 68(1), 83-87.

Menz, H.B., Fotoohabadi, M.R., Munteanu, S.E., Zammit, G.V. and Gilheany, M.F., 2013. Plantar pressures and relative lesser metatarsal lengths in older people with and without forefoot pain. *Journal of Orthopaedic Research* 31(3), 427-433.

Menz, H.B., Latt, M.D., Tiedemann, A., San Kwan, M.M. and 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. and Lord, S.R., 2001. Foot pain impairs balance and functional ability in community-dwelling older people. *Journal of the American Podiatric Medical Association* 91(5), 222-229.

Menz, H.B. and Lord, S.R., 2005a. Gait instability in older people with hallux valgus. *Foot & ankle international* 26(6), 483-489.

Menz, H.B. and Morris, M.E., 2005b. Determinants of disabling foot pain in retirement village residents. *Journal of the American Podiatric Medical Association* 95(6), 573-579.

Menz, H.B. and Morris, M.E., 2005c. Footwear characteristics and foot problems in older people. *Gerontology* 51(5), 346-351.

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

Menz, H.B., Morris, M.E. and Lord, S.R., 2005d. Foot and ankle characteristics associated with impaired balance and functional ability in older people. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 60(12), 1546-1552.

Menz, H.B., Morris, M.E. and Lord, S.R., 2006b. Foot and ankle risk factors for falls in older people: a prospective study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 61(8), 866-870.

Menz, H.B., Munteanu, S.E., Zammit, G.V. and Landorf, K.B., 2010. Foot structure and function in older people with radiographic osteoarthritis of the medial midfoot. *Osteoarthritis and cartilage* 18(3), 317-322.

Menz, H.B., Zammit, G.V. and Munteanu, S.E., 2007. Plantar pressures are higher under callused regions of the foot in older people. *Clinical and Experimental Dermatology: Clinical dermatology* 32(4), 375-380.

Meyers-Rice, B., Sugars, L., McPoil, T. and Cornwall, M.W., 1994. Comparison of three methods for obtaining plantar pressures in nonpathologic subjects. *Journal of the American Podiatric Medical Association* 84(10), 499-504.

Mickle, K.J., Munro, B.J., Lord, S., Menz, H.B. and Steele, J.R., 2009a. Are toe weakness and deformity associated with falls in older people.

Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B. and Steele, J.R., 2009b. ISB Clinical Biomechanics Award 2009: toe weakness and deformity increase the risk of falls in older people. *Clinical biomechanics* 24(10), 787-791.

Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B. and Steele, J.R., 2010a. Foot pain, plantar pressures, and falls in older people: a prospective study. *Journal of the American Geriatrics Society* 58(10), 1936-1940.

Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B. and Steele, J.R., 2010b. Foot shape of older people: implications for shoe design. *Footwear Science* 2(3), 131-139.

Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B. and Steele, J.R., 2011a. Gait, balance and plantar pressures in older people with toe deformities. *Gait & posture* 34(3), 347-351.

Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B. and Steele, J.R., 2011b. Soft tissue thickness under the metatarsal heads is reduced in older people with toe deformities. *Journal of Orthopaedic Research* 29(7), 1042-1046.

Mickle, K.J. and Steele, J.R., 2015. Obese older adults suffer foot pain and foot-related functional limitation. *Gait & posture* 42(4), 442-447.

Mikhail, E.M., Bethel, J.S. and McGlone, J.C., 2001. Introduction to modern photogrammetry. *New York*, 19.

Misu, S., Doi, T., Asai, T., Sawa, R., Tsutsumimoto, K., Nakakubo, S., Yamada, M. and Ono, R., 2014. Association between toe flexor strength and spatiotemporal gait parameters in community-dwelling older people. *Journal of neuroengineering and rehabilitation* 11(1), 143.

Mochimaru, M. and Kouchi, M., 2011. 4D measurement and analysis of plantar deformation during walking and running. *Footwear Science* 3(sup1), S109-S112.

Moghadam, M., Ashayeri, H., Salavati, M., Sarafzadeh, J., Taghipoor, K.D., Saeedi, A. and Salehi, R., 2011. Reliability of center of pressure measures of postural stability in healthy older adults: effects of postural task difficulty and cognitive load. *Gait & posture* 33(4), 651-655.

Morag, E. and Cavanagh, P.R., 1999. Structural and functional predictors of regional peak pressures under the foot during walking. *Journal of biomechanics* 32(4), 359-370.

Moyer, B., Chambers, A., Redfern, M.S. and Cham, R., 2006. Gait parameters as predictors of slip severity in younger and older adults. *Ergonomics* 49(4), 329-343.

Mueller, M. and Strube, M., 1996. Generalizability of in-shoe peak pressure measures using the F-scan system. *Clinical Biomechanics* 11(3), 159-164.

Mueller, M.J., Hastings, M., Commean, P.K., Smith, K.E., Pilgram, T.K., Robertson, D. and Johnson, J., 2003. Forefoot structural predictors of plantar pressures during walking in people with diabetes and peripheral neuropathy. *Journal of biomechanics* 36(7), 1009-1017.

Mueller, M.J., Sinacore, D.R., Hoogstrate, S. and Daly, L., 1994. Hip and ankle walking strategies: effect on peak plantar pressures and implications for neuropathic ulceration. *Archives of physical medicine and rehabilitation* 75(11), 1196-1200.

Mueller, S., Carlsohn, A., Mueller, J., Baur, H. and Mayer, F., 2016. Influence of obesity on foot loading characteristics in gait for children aged 1 to 12 years. *PLoS One* 11(2), e0149924.

Mundt, M., Batista, J.P., Markert, B., Bollheimer, C. and Laurentius, T., 2019. Walking with rollator: a systematic review of gait parameters in older persons. *European review of aging and physical activity* 16(1), 15.

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

Murphy, D.F., Beynnon, B.D., Michelson, J.D. and Vacek, P.M., 2005. Efficacy of plantar loading parameters during gait in terms of reliability, variability, effect of gender and relationship between contact area and plantar pressure. *Foot & ankle international* 26(2), 171-179.

Myerson, M. and Shereff, M., 1989. The pathological anatomy of claw and hammer toes. *JBJS* 71(1), 45-49.

Myronenko, A. and Song, X., 2010. Point set registration: Coherent point drift. *IEEE transactions on pattern analysis and machine intelligence* 32(12), 2262-2275.

Najafi, B., Khan, T., Fleischer, A. and Wrobel, J., 2013. The impact of footwear and walking distance on gait stability in diabetic patients with peripheral neuropathy. *Journal of the American Podiatric Medical Association* 103(3), 165-173.

Naraghi, R., Bryant, A. and Slack-Smith, L., 2014. Description of total population hospital admissions for Morton's metatarsalgia in Australia. *Journal of The American Podiatric Medical Association* 104(5), 451-454.

Nashner, L.M., 2014. Practical biomechanics and physiology of balance. *Balance Function Assessment and Management* 431.

Neri, S.G., Harvey, L.A., Tiedemann, A., Gadelha, A.B. and Lima, R.M., 2020a. Obesity and falls in older women: mediating effects of muscle quality, foot loads and postural control. *Gait & Posture* 77, 138-143.

Neri, S.G., Tiedemann, A., Gadelha, A.B. and Lima, R.M., 2020b. Body fat distribution in obesity and the association with falls: a cohort study of Brazilian women aged 60 years and over. *Maturitas*.

Neri, S.G.R., Gadelha, A.B., Correia, A.L.M., Pereira, J.C., de David, A.C. and Lima, R.M., 2017. Obesity is associated with altered plantar pressure distribution in older women. *Journal of Applied Biomechanics* 33(5), 323-329.

Neri, S.G.R., Gadelha, A.B., de David, A.C., Ferreira, A.P., Safons, M.P., Tiedemann, A. and Lima, R.M., 2019. The association between body adiposity measures, postural balance, fear of falling, and fall risk in older community-dwelling women. *Journal of geriatric physical therapy* 42(3), E94-E100.

Neri, S.G.R., Gadelha, A.B., Pereira, J.C., Gutierres Filho, P.J.B. and Lima, R.M., 2018. Obesity is associated with reduced postural control in community-dwelling older adults: a systematic review. *European Journal of Physiotherapy* 20(3), 178-186.

Neumanm, D.A. (2002) Kinesiology of the musculoskeletal system: foundations for physical rehabilitation, Mosby.

Nguyen, U.-S., Hillstrom, H.J., Li, W., Dufour, A.B., Kiel, D.P., Procter-Gray, E., Gagnon, M.M. and Hannan, M.T., 2010. Factors associated with hallux valgus in a population-based study of older women and men: the MOBILIZE Boston Study. *Osteoarthritis and cartilage* 18(1), 41-46.

Nix, S., Smith, M. and Vicenzino, B., 2010. Prevalence of hallux valgus in the general population: a systematic review and meta-analysis. *Journal of foot and ankle research* 3(1), 21.

Nix, S.E., Vicenzino, B.T., Collins, N.J. and Smith, M.D., 2013. Gait parameters associated with hallux valgus: a systematic review. *Journal of foot and ankle research* 6(1), 9.

Noce, H.P., 2005. An in-shoe instrument for acquisition and storage of plantar pressure.

Novak, B., Možina, J. and Jezeršek, M., 2014. 3D laser measurements of bare and shod feet during walking. *Gait & posture* 40(1), 87-93.

Oates, A.R., Frank, J.S. and Patla, A.E., 2010. Control of dynamic stability during adaptation to gait termination on a slippery surface. *Experimental brain research* 201(1), 47-57.

Oggier, T., Büttgen, B., Lustenberger, F., Becker, G., Rüegg, B. and Hodac, A., 2005. SwissRanger SR3000 and first experiences based on miniaturized 3D-TOF cameras. *Proc. of the First Range Imaging Research Day at ETH Zurich*.

Oh-Park, M., Kirschner, J., Abdelshahed, D. and Kim, D.D., 2019. Painful Foot Disorders in the Geriatric Population: A Narrative Review. *American journal of physical medicine & rehabilitation* 98(9), 811-819.

Oladeji, O., Stackhouse, C., Gracely, E. and Orlin, M., 2008. Comparison of the two-step and midgait methods of plantar pressure measurement in children. *Journal of the American Podiatric Medical Association* 98(4), 268-277.

Orendurff, M.S., Rohr, E.S., Segal, A.D., Medley, J.W., Green III, J.R. and Kadel, N.J., 2008. Regional foot pressure during running, cutting, jumping, and landing. *The American journal of sports medicine* 36(3), 566-571.

Orlin, M.N. and McPoil, T.G., 2000. Plantar pressure assessment. *Physical therapy* 80(4), 399-409.

Ortega, J.D. and Farley, C.T., 2015. Effects of aging on mechanical efficiency and muscle activation during level and uphill walking. *Journal of Electromyography and Kinesiology* 25(1), 193-198.

Ostrosky, K.M., VanSwearingen, J.M., Burdett, R.G. and Gee, Z., 1994. A comparison of gait characteristics in young and old subjects. *Physical therapy* 74(7), 637-644.

Owings, T.M. and Grabiner, M.D., 2004. Variability of step kinematics in young and older adults. *Gait & posture* 20(1), 26-29.

Pataky, T.C., Caravaggi, P., Savage, R., Parker, D., Goulermas, J.Y., Sellers, W.I. and Crompton, R.H., 2008. New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). *Journal of biomechanics* 41(9), 1987-1994.

Patel, K.V., Phelan, E.A., Leveille, S.G., Lamb, S.E., Missikpode, C., Wallace, R.B., Guralnik, J.M. and Turk, D.C., 2014. High prevalence of falls, fear of falling, and impaired balance in older adults with pain in the United States: findings from the 2011 National Health and Aging Trends Study. *Journal of the American Geriatrics Society* 62(10), 1844-1852.

Paterson, K., Hill, K. and Lythgo, N., 2011. Stride dynamics, gait variability and prospective falls risk in active community dwelling older women. *Gait & posture* 33(2), 251-255.

Perhamre, S., Janson, S., Norlin, R. and Klässbo, M., 2011. Sever's injury: treatment with insoles provides effective pain relief. *Scandinavian journal of medicine & science in sports* 21(6), 819-823.

Perry, J. and Burnfield, J.M., 1993. Gait analysis: normal and pathological function. *Developmental Medicine and Child Neurology* 35, 1122-1122.

Perry, J. and Davids, J.R., 1992. Gait analysis: normal and pathological function. *Journal of Pediatric Orthopaedics* 12(6), 815.

Perttunen, J. (2002) Foot loading in normal and pathological walking, University of Jyväskylä.

Petre, M.T. (2007) Investigating the internal stress/strain state of the foot using magnetic resonance imaging and finite element analysis, Case Western Reserve University.

Pham, H., Armstrong, D.G., Harvey, C., Harkless, L.B., Giurini, J.M. and Veves, A., 2000. Screening techniques to identify people at high risk for diabetic foot ulceration: a prospective multicenter trial. *Diabetes care* 23(5), 606-611.

Phethean, J. and Nester, C., 2012. The influence of body weight, body mass index and gender on plantar pressures: results of a cross-sectional study of healthy children's feet. *Gait & posture* 36(2), 287-290.

Piirtola, M. and Era, P., 2006. Force platform measurements as predictors of falls among older people–a review. *Gerontology* 52(1), 1-16.

Pijnappels, M., Reeves, N.D. and van Dieën, J.H., 2008. Identification of elderly fallers by muscle strength measures. *European journal of applied physiology* 102(5), 585-592.

Pitei, D., Foster, A. and Edmonds, M., 1999. The effect of regular callus removal on foot pressures. *The Journal of foot and ankle surgery* 38(4), 251-255.

Plank, M., 1995. The pattern of forefoot pressure distribution in hallux valgus. *The foot* 5(1), 8-14.

Plotnik, M., Bahat, Y., Akiva, Y., Gimmon, Y., Inzelberg, R. and Kizony, R. 2013 Can we climb with our eyes? Preliminary report on the effect of conflicting virtual scenery on leveled and inclined gait, pp. 210-211, IEEE.

Powell, D.W., Long, B., Milner, C.E. and Zhang, S., 2011. Frontal plane multi-segment foot kinematics in high-and low-arched females during dynamic loading tasks. *Human movement science* 30(1), 105-114.

Prince, F., Corriveau, H., Hébert, R. and Winter, D.A., 1997. Gait in the elderly. *Gait & posture* 5(2), 128-135.

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

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

Qin, L.-y., Ma, H. and Liao, W.-H. 2015 Insole plantar pressure systems in the gait analysis of post-stroke rehabilitation, pp. 1784-1789, IEEE.

Queen, R.M., Abbey, A.N., Wiegerinck, J.I., Yoder, J.C. and Nunley, J.A., 2010. Effect of shoe type on plantar pressure: a gender comparison. *Gait & posture* 31(1), 18-22.

Rajachandrakumar, R., Mann, J., Schinkel-Ivy, A. and Mansfield, A., 2018. Exploring the relationship between stability and variability of the centre of mass and centre of pressure. *Gait & posture* 63, 254-259.

Ramanathan, A., Kiran, P., Arnold, G., Wang, W. and Abboud, R., 2010. Repeatability of the Pedar-X® in-shoe pressure measuring system. *Foot and ankle surgery* 16(2), 70-73.

Ramirez-Bautista, J.A., Huerta-Ruelas, J.A., Chaparro-Cárdenas, S.L. and Hernández-Zavala, A., 2017. A review in detection and monitoring gait disorders using in-shoe plantar measurement systems. *IEEE reviews in biomedical engineering* 10, 299-309.

Ranu, H.S., 1986. Miniature load cells for the measurement of foot-ground reaction forces and centre of foot pressure during gait. *Journal of biomedical engineering* 8(2), 175-177.

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

Raymakers, R. and Waugh, W., 1971. The treatment of metatarsalgia with hallux valgus. *The Journal of bone and joint surgery. British volume* 53(4), 684-687.

Razak, A., Hadi, A., Zayegh, A., Begg, R.K. and Wahab, Y., 2012. Foot plantar pressure measurement system: A review. *Sensors* 12(7), 9884-9912.

Remondino, F. and Fraser, C., 2006. Digital camera calibration methods: considerations and comparisons. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 36(5), 266-272.

Richards, R. 1991 Calluses, corns, and shoes, pp. 112-114.

Riva, D., Mamo, C., Fanì, M., Saccavino, P., Rocca, F., Momenté, M. and Fratta, M., 2013. Single stance stability and proprioceptive control in older adults living at home: gender and age differences. *Journal of aging research* 2013.

Robinson, C.C., Balbinot, L.F., Silva, M.F., Achaval, M. and Zaro, M.A. 2013 Plantar pressure distribution patterns of individuals with prediabetes in comparison with healthy individuals and individuals with diabetes, SAGE Publications Sage CA: Los Angeles, CA.

Rodgers, M.M., 1995. Dynamic foot biomechanics. *Journal of Orthopaedic & Sports Physical Therapy* 21(6), 306-316.

Rodrigo, A.S., Goonetilleke, R.S. and Xiong, S., 2013. Load distribution to minimise pressure-related pain on foot: a model. *Ergonomics* 56(7), 1180-1193.

Rodríguez-Sanz, D., Tovaruela-Carrión, N., López-López, D., Palomo-López, P., Romero-Morales, C., Navarro-Flores, E. and Calvo-Lobo, C., 2018. Foot disorders in the elderly: A mini-review. *Disease-a-Month* 64(3), 64-91.

Rosenbaum, D. and BECKER, H.P., 1997. Plantar pressure distribution measurements. Technical background and clinical applications. *Foot and ankle surgery* 3(1), 1-14.

Rosenbaum, D., Hautmann, S., Gold, M. and Claes, L., 1994. Effects of walking speed on plantar pressure patterns and hindfoot angular motion. *Gait & posture* 2(3), 191-197.

Rozema, A., Ulbrecht, J.S., Pammer, S.E. and Cavanagh, P.R., 1996. In-shoe plantar pressures during activities of daily living: implications for therapeutic footwear design. *Foot & ankle international* 17(6), 352-359.

Rubenstein, L.Z., 2006. Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and ageing* 35(suppl_2), ii37-ii41.

Sage, R.A., Webster, J.K. and Fisher, S.G., 2001. Outpatient care and morbidity reduction in diabetic foot ulcers associated with chronic pressure callus. *Journal of the American Podiatric Medical Association* 91(6), 275-279.

Saggin, B., Scaccabarozzi, D. and Tarabini, M., 2013. Metrological performances of a plantar pressure measurement system. *IEEE Transactions on Instrumentation and Measurement* 62(4), 766-776.

Samson, M.M., Crowe, A., De Vreede, P., Dessens, J.A., Duursma, S.A. and Verhaar, H.J., 2001. Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight. *Aging clinical and experimental research* 13(1), 16-21.

Samson, W., Van Hamme, A., Sanchez, S., Chèze, L., Jan, S.V.S. and Feipel, V., 2014. Foot roll-over evaluation based on 3D dynamic foot scan. *Gait & posture* 39(1), 577-582.

Scaglioni-Solano, P. and Aragón-Vargas, L.F., 2015. Age-related differences when walking downhill on different sloped terrains. *Gait & Posture* 41(1), 153-158.

Schmeltzpfenning, T., Plank, C., Fritz, B., Aswendt, P. and Grau, S., 2011. 3D dynamic behaviour of foot structure may provide additional information for last design. *Footwear Science* 3(sup1), S147-S148.

Schmeltzpfenning, T., Plank, C., Krauss, I., Aswendt, P. and Grau, S., 2009. Dynamic foot scanning: A new approach for measurement of the human foot shape while walking.

Schwartz, M.H., Rozumalski, A. and Trost, J.P., 2008. The effect of walking speed on the gait of typically developing children. *Journal of biomechanics* 41(8), 1639-1650.

Scott, G., Menz, H.B. and Newcombe, L., 2007. Age-related differences in foot structure and function. *Gait & posture* 26(1), 68-75.

Segal, A., Rohr, E., Orendurff, M., Shofer, J., O'Brien, M. and Sangeorzan, B., 2004. The effect of walking speed on peak plantar pressure. *Foot & Ankle International* 25(12), 926-933.

Sendur, S.N., Oguz, S., Dagdelen, S. and Erbas, T., 2019. Assessment of static and dynamic plantar data of patients with acromegaly. *Pituitary* 22(4), 373-380.

Sheehan, R.C. and Gottschall, J.S., 2012. At similar angles, slope walking has a greater fall risk than stair walking. *Applied ergonomics* 43(3), 473-478.

Shimba, T., 1984. An estimation of center of gravity from force platform data. *Journal of biomechanics* 17(1), 53-60.

Shkuratova, N., Morris, M.E. and Huxham, F., 2004. Effects of age on balance control during walking. *Archives of physical medicine and rehabilitation* 85(4), 582-588.

Simpson, K., Jiang, P., Shewokis, P., Odum, S. and Reeves, K., 1993. Kinematic and plantar pressure adjustments to downhill gradients during gait. *Gait & Posture* 1(3), 172-179.

Sneyers, C.J.L., Lysens, R., Feys, H. and Andries, R., 1995. Influence of malalignment of feet on the plantar pressure pattern in running. *Foot & ankle international* 16(10), 624-632.

Soames, R., 1985. Foot pressure patterns during gait. *Journal of biomedical engineering* 7(2), 120-126.

Sobhani, S., van den Heuvel, E.R., Dekker, R., Postema, K., Kluitenberg, B., Bredeweg, S.W. and Hijmans, J.M., 2017. Biomechanics of running with rocker shoes. *Journal of science and medicine in sport* 20(1), 38-44.

Sole, G., Pataky, T., Sole, C.C., Hale, L. and Milosavljevic, S., 2017. Age-related plantar centre of pressure trajectory changes during barefoot walking. *Gait & Posture* 57, 188-192.

Song, Q., Xu, K., Yu, B., Zhang, C., Sun, W. and Mao, D., 2015. Could insoles offload pressure? An evaluation of the effects of arch-supported functional insoles on plantar pressure distribution during race walking. *Research in Sports Medicine* 23(3), 278-288.

Sousa, A.S., Macedo, R., Santos, R., Sousa, F., Silva, A. and Tavares, J.M.R., 2016. Influence of prolonged wearing of unstable shoes on upright standing postural control. *Human movement science* 45, 142-153.

Spooner, S.K., Smith, D.K. and Kirby, K.A., 2010. In-shoe pressure measurement and foot orthosis research: A giant leap forward or a step too far? *Journal of the American Podiatric Medical Association* 100(6), 518-529.

Stess, R.M., Jensen, S.R. and Mirmiran, R., 1997. The role of dynamic plantar pressures in diabetic foot ulcers. *Diabetes care* 20(5), 855-858.

Stevens, J.A., 2005. Falls among older adults—risk factors and prevention strategies. *Journal of safety research* 36(4), 409-411.

Stewart, C., Leveille, S.G., Shmerling, R.H., Samelson, E.J., Bean, J.F. and Schofield, P., 2012. Management of persistent pain in older adults: the MOBILIZE Boston Study. *Journal of the American Geriatrics Society* 60(11), 2081-2086.

Stewart, S., Dalbeth, N., Vandal, A.C. and Rome, K., 2016. Spatiotemporal gait parameters and plantar pressure distribution during barefoot walking in people with gout and asymptomatic hyperuricemia: comparison with healthy individuals with normal serum urate concentrations. *Journal of foot and ankle research* 9(1), 1.

Stöckel, T., Jacksteit, R., Behrens, M., Skripitz, R., Bader, R. and Mau-Moeller, A., 2015. The mental representation of the human gait in young and older adults. *Frontiers in psychology* 6, 943.

Stolze, H.-J.F., Kirsten Steinauer, Peter Vieregge, Henning, 2000. Stride parameters in healthy young and old women-measurement variability on a simple walkway. *Experimental aging research* 26(2), 159-168.

Streiner, D.L., Norman, G.R. and Cairney, J. (2015) Health measurement scales: a practical guide to their development and use, Oxford University Press, USA.

Stubbs, B., Binnekade, T., Eggermont, L., Sepehry, A.A., Patchay, S. and Schofield, P., 2014. Pain and the risk for falls in community-dwelling older adults: systematic review and meta-analysis. *Archives of physical medicine and rehabilitation* 95(1), 175-187. e179.

Studenski, S., Perera, S., Patel, K., Rosano, C., Faulkner, K., Inzitari, M., Brach, J., Chandler, J., Cawthon, P. and Connor, E.B., 2011. Gait speed and survival in older adults. *Jama* 305(1), 50-58.

Stürmer, M., Becker, G. and Hornegger, J. 2011a Assessment of Time-of-Flight Cameras for Short Camera-Object Distances, pp. 231-238.

Sturmer, M., Penne, J. and Hornegger, J. 2008 Standardization of intensity-values acquired by time-of-flight-cameras, pp. 1-6, IEEE.

Stürmer, M., Seiler, C., Becker, G. and Hornegger, J. 2011b Alignment of multiple Time-of-Flight 3D Cameras for Reconstruction of walking feet.

Sturnieks, D.L., St George, R. and Lord, S.R., 2008. Balance disorders in the elderly. *Neurophysiologie Clinique/Clinical Neurophysiology* 38(6), 467-478.

Sun, J., Walters, M., Svensson, N. and Lloyd, D., 1996. The influence of surface slope on human gait characteristics: a study of urban pedestrians walking on an inclined surface. *Ergonomics* 39(4), 677-692.

Sutherland, D., 1994. Kinematics of normal human walking. *Human walking*.

Sutherland, D.H., 2005. The evolution of clinical gait analysis part III–kinetics and energy assessment. *Gait & posture* 21(4), 447-461.

Sutkowska, E., Sutkowski, K., Sokołowski, M., Franek, E. and Dragan, S., 2019. Distribution of the highest plantar pressure regions in patients with diabetes and its association with peripheral neuropathy, gender, age, and BMI: one centre study. *Journal of diabetes research* 2019.

Tanaka, T., Noriyasu, S., Ino, S., Ifukube, T. and Nakata, M., 1996. Objective method to determine the contribution of the great toe to standing balance and preliminary observations of age-related effects. *IEEE Transactions on Rehabilitation Engineering* 4(2), 84-90.

Tang, U.H., Zügner, R., Lisovskaja, V., Karlsson, J., Hagberg, K. and Tranberg, R., 2015. Foot deformities, function in the lower extremities, and plantar pressure in patients with diabetes at high risk to develop foot ulcers. *Diabetic foot & ankle* 6(1), 27593.

Taylor, A.J., Menz, H.B. and Keenan, A.-M., 2004. The influence of walking speed on plantar pressure measurements using the two-step gait initiation protocol. *The foot* 14(1), 49-55.

Telfer, S. and Woodburn, J., 2010. The use of 3D surface scanning for the measurement and assessment of the human foot. *Journal of foot and ankle research* 3(1), 1-9.

Teoh, J.C. and Lee, T., 2020. Identification of potential plantar ulceration among diabetes patients using plantar soft tissue stiffness. *Journal of the Mechanical Behavior of Biomedical Materials* 103, 103567.

Thabet, A.K., Trucco, E., Salvi, J., Wang, W. and Abboud, R.J., 2014. Dynamic 3D shape of the plantar surface of the foot using coded structured light: a technical report. *Journal of foot and ankle research* 7(1), 5.

Thaler-Kall, K., Peters, A., Thorand, B., Grill, E., Autenrieth, C.S., Horsch, A. and Meisinger, C., 2015. Description of spatio-temporal gait parameters in elderly people and their association with history of falls: results of the population-based cross-sectional KORA-Age study. *BMC geriatrics* 15(1), 32.

Thomas, J.L., Blitch, E.L., Chaney, D.M., Dinucci, K.A., Eickmeier, K., Rubin, L.G., Stapp, M.D. and Vanore, J.V., 2009. Diagnosis and treatment of forefoot disorders. Section 2. Central metatarsalgia. *The Journal of foot and ankle surgery* 48(2), 239-250.

Thomas, S. and Barrington, R., 2003. Hallux valgus. *Current Orthopaedics* 17(4), 299-307.

Thompson, P.D., Buchner, D., Piña, I.L., Balady, G.J., Williams, M.A., Marcus, B.H., Berra, K., Blair, S.N., Costa, F. and Franklin, B., 2003. Exercise and physical activity in the prevention and treatment of atherosclerotic cardiovascular disease: a statement from the Council on Clinical Cardiology (Subcommittee on Exercise, Rehabilitation, and Prevention) and the Council on Nutrition, Physical Activity, and Metabolism (Subcommittee on Physical Activity). *Circulation* 107(24), 3109-3116.

Tinetti, M.E., Speechley, M. and Ginter, S.F., 1988. Risk factors for falls among elderly persons living in the community. *New England journal of medicine* 319(26), 1701-1707.

Tirosh, O. and Sparrow, W., 2005. Age and walking speed effects on muscle recruitment in gait termination. *Gait & posture* 21(3), 279-288.

Topper, A., Maki, B. and Holliday, P.J., 1993. Are activity-based assessments of balance and gait in the elderly predictive of risk of falling and/or type of fall? *Journal of the American Geriatrics Society* 41(5), 479-487.

Tovaruela-Carrión, N., López-López, D., Losa-Iglesias, M.E., Álvarez-Ruíz, V., Melero-González, G., Calvo-Lobo, C. and Becerro-de Bengoa-Vallejo, R., 2018. Comparison of health-related quality of life between patients with different metatarsalgia types and matched healthy controls: a cross-sectional analysis. *Sao Paulo Medical Journal* 136(5), 464-471.

Trombini-Souza, F., Kimura, A., Ribeiro, A.P., Butugan, M., Akashi, P., Passaro, A.C., Arnone, A.C. and Sacco, I.C., 2011. Inexpensive footwear decreases joint loading in elderly women with knee osteoarthritis. *Gait & posture* 34(1), 126-130.

Tsung, B.Y.S., Zhang, M., Mak, A.F.T. and Wong, M.W.N., 2004. Effectiveness of insoles on plantar pressure redistribution. *Journal of rehabilitation research and development*.

Tuna, H., Yildiz, M., Celtik, C. and Kokino, S., 2004. Static and dynamic plantar pressure measurements in adolescents. *Acta orthopaedica et traumatologica turcica* 38(3), 200-205.

Udin, W.S. and Ahmad, A. 2011 Calibration of high resolution digital camera using self-calibration bundle adjustment method, pp. 137-141, IEEE.

Urry, S., 1999. Plantar pressure-measurement sensors. *Measurement Science and Technology* 10(1), R16.

Urry, S.R., 2002. Redistribution of foot pressure in healthy adults during sideslope walking. *Foot & ankle international* 23(12), 1112-1118.

Uzun, A., 2013. The effect of basketball on the sole contact areas and maximal forces of elite basketball players. *Energy Education Science and Technology Part B: Social and Educational Studies* 5(1), 633-640.

Vallabhajosula, S., Humphrey, S.K., Cook, A.J. and Freund, J.E., 2019. Concurrent validity of the Zeno walkway for measuring spatiotemporal gait parameters in older adults. *Journal of geriatric physical therapy* 42(3), E42-E50.

van der Leeden, M., Dekker, J.H., Siemonsma, P.C., Lek-Westerhof, S.S. and Steultjens, M.P., 2004. Reproducibility of plantar pressure measurements in patients with chronic arthritis: a comparison of one-step, two-step, and three-step protocols and an estimate of the number of measurements required. *Foot & ankle international* 25(10), 739-744.

Van Netten, J., Price, P.E., Lavery, L., Monteiro-Soares, M., Rasmussen, A., Jubiz, Y., Bus, S. and Foot, I.W.G.o.t.D., 2016. Prevention of foot ulcers in the at-risk patient with diabetes: a systematic review. *Diabetes/Metabolism Research and Reviews* 32, 84-98.

Vaughan, C., Davis, B. and O'CONNOR, J., 1999. Dynamics of human gait 2nd edition.

Verdu-Roman, C., Sanz-Reig, J., Martinez-Gimenez, E., Orozco-Beltran, D., Quesada, J.A., Lopez-Pineda, A., Gil-Guillen, V.F. and Carratala-Munuera, C., 2019. Association between preoperative dynamic plantar pressures and clinical outcomes at 6 months after hallux valgus surgery. *Fuß & Sprunggelenk* 17(2), 75-86.

Veves, A., Murray, H., Young, M. and Boulton, A., 1992. The risk of foot ulceration in diabetic patients with high foot pressure: a prospective study. *Diabetologia* 35(7), 660-663.

Vieira, M.F., Rodrigues, F.B., e Souza, G.S.d.S., Magnani, R.M., Lehnen, G.C., Campos, N.G. and Andrade, A.O., 2017. Gait stability, variability and complexity on inclined surfaces. *Journal of biomechanics* 54, 73-79.

Waaijman, R., de Haart, M., Arts, M.L., Wever, D., Verlouw, A.J., Nollet, F. and Bus, S.A., 2014. Risk factors for plantar foot ulcer recurrence in neuropathic diabetic patients. *Diabetes care* 37(6), 1697-1705.

Waldecker, U., 2002. Metatarsalgia in hallux valgus deformity: a pedographic analysis. *The Journal of foot and ankle surgery* 41(5), 300-308.

Wallace, J., White, H., Augsburger, S., Shapiro, R. and Walker, J., 2018. Foot pressure analysis using the emed® in typically developing children and adolescents: A summary of current techniques and typically developing cohort data for comparison with pathology. *The Foot* 37, 28-37.

Walsh, T.P., Butterworth, P.A., Urquhart, D.M., Cicuttini, F.M., Landorf, K.B., Wluka, A.E., Shanahan, E.M. and 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.

Wang, C.L., Hsu, T.C., Shau, Y.W., Shieh, J.Y. and Hsu, K.H., 1999. Ultrasonographic measurement of the mechanical properties of the sole under the metatarsal heads. *Journal of orthopaedic research* 17(5), 709-713.

Wang, L., Ning, H., Tan, T. and Hu, W., 2004. Fusion of static and dynamic body biometrics for gait recognition. *IEEE Transactions on Circuits and Systems for Video Technology* 14(2), 149-158.

Wei, W., Xu, C., Yang, X.-J., Lu, C.-B., Lei, W. and Zhang, Y., 2020. Analysis of Dynamic Plantar Pressure before and after the Occurrence of Neurogenic Intermittent Claudication in Patients with Lumbar Spinal Stenosis: An Observational Study. *BioMed Research International* 2020.

Werd, M.B., Knight, E.L. and Langer, P.R. (2010) Athletic footwear and orthoses in sports medicine, Springer.

Werner, C., Lindquist, A., Bardeleben, A. and Hesse, S., 2007. The influence of treadmill inclination on the gait of ambulatory hemiparetic subjects. *Neurorehabilitation and neural repair* 21(1), 76-80.

Wervey, R.A., Harris, G.F. and Wertsch, J.J. 1997 Plantar pressure characteristics during stair climbing and descent, pp. 1746-1748, IEEE.

Winter, D.A., 1995a. Anatomy, biomechanics and control of balance during standing and walking. *Waterloo, Canada: Graphic Services*.

Winter, D.A., 1995b. Human balance and posture control during standing and walking. *Gait & posture* 3(4), 193-214.

Winter, D.A., Patla, A.E., Frank, J.S. and Walt, S.E., 1990. Biomechanical walking pattern changes in the fit and healthy elderly. *Physical therapy* 70(6), 340-347.

Woledge, R.C., Birtles, D.B. and Newham, D.J., 2005. The variable component of lateral body sway during walking in young and older humans. *The Journals of*

Gerontology Series A: Biological Sciences and Medical Sciences 60(11), 1463-1468.

Wolf, P.R., Dewitt, B.A. and Wilkinson, B.E. (2014) Elements of Photogrammetry with Applications in GIS, McGraw-Hill Education.

Wong, L., Hunt, A., Burns, J. and Crosbie, J., 2008. Effect of foot morphology on center-of-pressure excursion during barefoot walking. *Journal of the American Podiatric Medical Association* 98(2), 112-117.

Wong, P.-l., Chamari, K., Wisløff, U. and Hong, Y., 2007. Higher plantar pressure on the medial side in four soccer-related movements. *British journal of sports medicine* 41(2), 93-100.

Woodburn, J. and Helliwell, P., 1996. Observations on the F-Scan in-shoe pressure measuring system. *Clinical Biomechanics* 11(5), 301-304.

Woollacott, M.H. and Pei-Fang, T., 1997. Balance control during walking in the older adult: research and its implications. *Physical therapy* 77(6), 646.

Xu, L., Zeng, H., Zhao, J., Zhao, J., Yin, J., Chen, H., Chai, Y., Bao, Y., Liu, F. and Jia, W., 2019. Index of Plantar Pressure Alters with Prolonged Diabetes Duration. *Diabetes Therapy* 10(6), 2139-2152.

Yan, S.-h., Zhang, K., Tan, G.-q., Yang, J. and Liu, Z.-c., 2013. Effects of obesity on dynamic plantar pressure distribution in Chinese prepubescent children during walking. *Gait & posture* 37(1), 37-42.

Yan, S., Li, R., Shi, B., Wang, R. and Yang, L., 2020. Mixed factors affecting plantar pressures and center of pressure in obese children: obesity and flatfoot. *Gait & Posture*.

Yan, S., Ren, W., Liang, X. and Zhang, K. 2014 Gait characteristics of overweight and obese children with different ages, pp. 184-188, IEEE.

Yokozuka, M., Miki, C., Kurogo, H., Kobayashi, T., Nagai, M. and Katsura, R., 2019. Foot Characteristics and Falls among Community-dwelling Independent Elderly Women Who Can Walk Outdoors. *Progress in Rehabilitation Medicine* 4, 20190017.

Yoshida-Intern, S., 2007. A global report on falls prevention epidemiology of falls. *Geneva: WHO*.

Yoshida, Y., Saito, S., Aoki, Y., Kouchi, M. and Mochimaru, M. 2012 Shape completion and modeling of 3D foot shape while walking, pp. 1-3, IEEE.

Yu, X., Yu, G., Chen, Y. and Liu, X., 2011. The characteristics and clinical significance of plantar pressure distribution in patients with diabetic toe deformity: a dynamic plantar pressure analysis. *Journal of International Medical Research* 39(6), 2352-2359.

Zamboni, M., Mazzali, G., Zoico, E., Harris, T.B., Meigs, J.B., Di Francesco, V., Fantin, F., Bissoli, L. and Bosello, O., 2005. Health consequences of obesity in the elderly: a review of four unresolved questions. *International journal of obesity* 29(9), 1011.

Zammit, G.V., Menz, H.B. and 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. and 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.

Zijlstra, W., 2004. Assessment of spatio-temporal parameters during unconstrained walking. *European journal of applied physiology* 92(1-2), 39-44.

Appendix A

Ethics Clearance Forms

A.1 Participant Information Sheet

The University of Southern Queensland

Participant Information Sheet

TO: Participants

Human Research Ethics ID: H18REA160

Full Project Title: 3D Gait Phase Image and Plantar Pressure Comparison between Adults and Older Adults

Principal Researcher: Dr. Albert Chong

Student Researcher: Nibras Sabih Abbas

Associate Researcher(s):

This PhD research involves innovative techniques to perform the correlation between human 3D gait phase images and the corresponding plantar pressure images. These techniques are used to distinguish the difference of the gait characteristics between adults and older adults.

I am a postgraduate student working on Doctoral research at the University of Southern Queensland (USQ). We would like to invite you to participate in this research project because we would like to develop an accurate photogrammetric approach which provides low-cost, high-quality 3D models of human lower limb and foot with the corresponding plantar pressure models during gait for both adults and older adults subjects. This can provide a full comparison and evaluation of the gait trial based on barefoot of adults and older adults participated in this study. You as a participant should read this plain language statement carefully. The purpose of this statement is to explain to you as openly and clearly as possible all the procedures involved so that you can make a fully informed decision whether you are willing to participate. You should feel free to ask your inquiries regarding information stated in this document. You may also wish to discuss the project with a relative, friend, or your local health worker. Once you understand what the project is about and decide to agree to take part in it, it is required to sign the Consent Form. By signing the Consent Form, you indicate understanding the information and giving your consent to participate in the research project.

1. **Research Purpose**

Due to age-related deterioration of the balance and neuromuscular systems, falls experienced by older people during gait, could result in serious injuries. The risk of falls sustained by older people can be increased because of stability and balance impairment caused by any factor, which in turn may impair the foot function during normal gait. This investigation involves innovative techniques to perform the correlation between human 3D gait phase images and the corresponding plantar pressure images. The outcomes of the research will be: 1) improved techniques for precise measurement and analysis of human lower limb during gait; 2) improved method for precisely measurement of human plantar pressure parameters; and 3) improved correlation technique between 3D surface models and plantar pressure data to observe the difference in gait characteristics between adults and older adults.

2. **Procedures**

- You will be informed by a description of the whole test prior to conducting the test and you will decide if you will to participate. In addition, the researcher will ask you prior to being able to participate whether you suffer from any abnormality with your normal gait to indicate whether you can be considered as healthy subjects.
- You will be asked doing a number of foot measurements. This can include measuring foot length and width and the distance from heel point to the second metatarsal bone point. This data will be used in data analysis with other obtained data, 3D model of human lower limb and foot along with plantar pressure data. You will be informed the details of all steps before the commencement of the test.

- 50 minutes as an approximate time will be required for each full tests to be undertaken. You have the right to choose depending on your available time within normal working hours. However, you are able to participate outside of working hours if you desire. The data will be collected at the University of Southern Queensland (Toowoomba campus Lab or Ipswich campus Lab).
- Five video cameras (Panasonic Lumix DMC-FZ300 Digital Camera) will be utilised in the close-up photogrammetric multi stereo-video recording. Then, the calculation of the measurements of human lower limb movement will be obtained for both adults and older adults by putting markers on subjects' lower limb and feet. You will be asked to perform the normal human walking on the walkway. The test starts by the position of standard human standing, followed by proceeding forward and stepping with the left foot on a TekScan floor pressure mat where the second step will be recorded. The plantar parameters, such as contact area, contact pressure, and pressure-time integral will be captured by a MatScan® (Tekscan, Boston, MA) plantar-pressure mapping system.
- The test will be repeated three to five times (each time for 15 seconds) for each participant so a reliable plantar pressure data can be obtained. In order to ensure that the correct foot was placed on the floor-mat without alteration of the gait, you will be given three to five minutes to practice walking and procedure before starting the test.
- You have the full rights to accept or decline to take part in this research or even withdraw from the research at any stage in which you fell you want to do that and your data will be destroyed instantly.

3. <u>Confidentiality</u>

Any obtained information related to this project which can identify you will remain confidential. The information will be only disclosed with your permission, subjected to legal requirements.

If you admit your permission through signing the Consent Form, the results obtained from the tests of the research project will be published in scientific journals and conferences.

In publications, your information will be provided and exhibited in a way that you cannot be identified. Signing the Consent Form will secure your information from being identified anywhere. However, the information may be known to the research group.

The results required to be published will not target individuals, hence your name or images that could lead to identifying you will not be used. No personal information will be collected except your height, weight, age, and some foot measurements. In addition, only lower limb and foot will be imaged.

The acquired data from this research might be used for further research and this depends on the possibility of enhancing or further improving the computation of obtained data to obtain further developed data that can be beneficial for future research.

4. <u>Voluntary Participation</u>

Participation is entirely voluntary. If you do not wish to take part, you are not obliged to.

If you decide to take part and then you find that you want to withdraw, you should feel free to withdraw from the project at any stage. In this case, any information already obtained from your test will be destroyed. As you are not identifiable, it is up to you to decide whether you agree to keep your related data for research purpose.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your relationship with the University of Southern Queensland.

Before you can make your decision, a member of the research team will be available to answer any questions you have about the research project. You have the right to ask for any kind of information regarding the research project tests. Once you have had a chance to ask your queries and have received satisfactory answers, you are welcome to sign the Consent Form.

If you decide to withdraw from this research project, please notify a member of the research team. This notice will allow the research team to inform you whether there are any related requirements linked to withdrawing process.

Thank you for taking the time to help with this research project. Please keep this sheet for your information.

5. Queries or Concerns

If you have any queries regarding the research project, you can contact the principal researcher:

Nibras Abbas
Faculty of Health, Engineering and Sciences
University of Southern Queensland
West Street, Toowoomba 4350
Email: Nibras.Abbas@usq.edu.au

For any other concerns or complaints regarding the conduct of the project:

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**. The Manager of Research Integrity and Ethics is not connected with the research project and can facilitate a resolution to your concern in an unbiased manner.

A.2 Consent Form

The University of Southern Queensland

Consent Form

TO: Participants

Human Research Ethics ID: H18REA160

Full Project Title: 3D Gait Phase Image and Plantar Pressure Comparison between Adults and Older Adults

Principal Researcher: Dr. Albert Chong

Student Researcher: Nibras Sabih Abbas

Associate Researcher(s):

- 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 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 my lower limb and foot will be videotaped and photographed during the test of this study.

Name of participant

……………………………………………………………………………………….

Signed …………………………………………………………………………

Date ………………………………………………………………………….

If you have any ethical concerns with how the research is being conducted or any queries about your rights as a participant, please feel free to contact the University of Southern Queensland Ethics Officer on the following details.

Ethics and Research Integrity Officer
Office of Research and Higher Degrees
University of Southern Queensland
West Street, Toowoomba 4350
Phone number: +61 7 4631 2690
Email: human.ethics@usq.edu.au