THE EFFECT OF LOAD CARRIAGE WHILE WEARING HIGH-HEELED SHOES ON ANKLE JOINT DURING LEVEL AND UPHILL WALKING

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Biomedical Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"THE EFFECT OF LOAD CARRIAGE WHILE WEARING HIGH-HEELED SHOES ON ANKLE JOINT DURING LEVEL AND UPHILL WALKING"** was prepared by **TAN YING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Biomedical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

A within-subject comparative study of back pack load carriage while walking in different shoe and slope condition was performed to determine and identify the biomechanics effects on ankle joint while wearing high-heeled shoes during level and uphill walking with the effect of load carriage. Kinetic and kinematic data of 15 subjects walked in barefoot and high-heeled shoes with the selection of their preferable walking speed has been collected. Inverse dynamic method had been applied to calculate the ankle joint force and Achilles tendon force. All of the data collected had been normalized to minimize the bias of subject and statistical t-test had been performed to compare the difference between each variables. Result revealed that heel height significantly affects the ankle kinetic, where greater VGRF and ankle joint force were produced, and lower Achilles tendon force was produced as the heel height increases. Next, backpack load carriage also significantly affects the ankle kinetic, as greater VGRF and ankle joint force were experienced by the subjects and lower Achilles tendon force was found when the weight of load increases. On the other hand, the increment of slope level significantly affects the ankle kinetic, where greater VGRF and Achilles tendon force were experienced in level condition with lesser ankle joint force. Cadence, stride length and step length were reduced as the heel height, loaded backpack carriage and inclined slope increases.

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LIST OF SYMBOLS / ABBREVIATIONS

a	heel height, m
b	length of heel to ankle, m
c	foot length, m
d	length of ankle to COM, m
e	length of heel tip to ankle in horizontal direction, m
f	moment arm of COM, m
g	gravity acceleration, m/s^2
i	length of heel tip to ankle in vertical direction, m
l_o	leg length, m
m	segmental mass of foot, kg
m_{body}	body mass, kg
σ	angle between high-heeled shoe and inclined plane, °
θ	Achilles tendon force angle, °
α	ankle, COM and heel angle, °
β	angle of elevation, °
γ	angle of COM of mg, °
F_{AT}	Achilles tendon force, N
A	ankle joint force, N
BMI	body mass index, kg/m^2
VGRF	vertical ground reaction force, N
COM	center of mass, m
M	moment, N·m

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

High-heeled shoes can be defined as a shoe when the elevation of the heel is higher than the fore-part and raised higher off the ground compared to the toe. Despite numerous problems in comfort and support, high-heeled shoes remain highly popular that most of the women wear them on a daily basis (Barkema, Derrick and Martin, 2012). Researches showed that wearing high-heeled shoes regularly will cause unbalance distribution of load beneath the foot and will have deleterious effect to the foot structure (Speksnijder, et al., 2005). Detrimental effects suffered by fellow women are not only caused by the heel height, but also the load carriage and the degree of walking, either level or uphill walking. Studies showed that load carriage will increase the joint moments and also powers while wearing high-heeled shoes (Dames and Smith, 2016), which will lead to imbalance posture and gait movement of women. Since early 1930s, researches started analysing and investigating the variation of loads beneath the foot with different heel height (Speksnijder, et al., 2005). Despite the height of the heel, wearing high-heeled shoes will give rise to the alterations in balance. Certainly, compared to barefoot, the design of the heels creates inconvenience and difficulties in balancing and will raise the risk of falling as there is alteration in the centre of mass (COM) and the decrement of the base of support (BOS) (Di Sipio, et al., 2018).

Walking, which is also known as ambulation, is a famous moderate intensity physical activity among human and said to be the most preferred outdoor recreational activity (Barton, Hine and Pretty, 2009) where it brings substantial importance to the public health. One of the solutions to chronic disease and rising health protection is just simple by walking every day (Lee and Buchner, 2008). Figure 1.1 below shows the gait cycle of walking normally. One gait cycle can be expressed in stance phase and swing phase, where one complete gait cycle is measured from heel strike to heel strike. Almost 60% of one complete gait cycle is spent in the stance phase as it is the time period when the foot is over ground. During stance phase, the leg supports the body weight and provides support for single limb. Another 40% of the complete gait cycle goes to the swing phase, where it is the time period when the foot is off the ground and moving forward. During swing phase, the limb advances. Stride length is the measurement of distance between the consecutive initial contacts of the same foot over ground while step length is the measurement of distance between the initial contacts of the alternating feet.

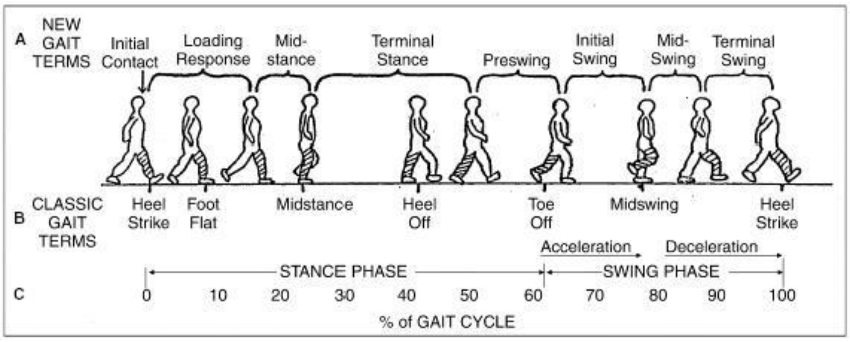

Figure 1.1: Gait Cycle (Orthobullets, 2016).

1.2 Importance of the Study

Previous studies merely focus on the effects on lower extremities caused by high-heeled shoes, different types of load carriage or combination of both high-heeled shoes and types of load carriage. However, the resources and studies regarding effects on lower extremities caused by the combination above correlative with uphill walking are limited. Thus, in this study, the effects of load carriage while wearing high-heeled shoes on ankle joint during level and uphill walking will be discussed and determined by analysing the data obtained using the forced plate embedded treadmill. The findings can provide a better understanding to the public and show the difference between level and uphill walking associated with load carriage and high-heeled shoes to the ankle joint. Moreover, this project can also be used to study on the result that reflects on Asian young adults' gait. This benefits the public to increase their understanding and knowledge towards their lower extremities and also ease future researchers to complete their studies.

1.3 Problem Statement

Footwear is the primary component that provides shock attenuation (McPoil Jr, 1988). Yet, according to studies, there is no cushioning provided at the heel strike which can directly transfer the contact force to the body in pin-point high-heeled shoe (Lee and Li, 2014). Researches shown that in terms of kinetic and kinematic effects, different heel height and load carrying generate different effects to the joint of the lower extremities (Chan, Chia and Tan, 2018). However, biomechanics studies on the effects with combination of load carrying, high-heeled shoes wearing and inclined walking are limited and insufficient. Thus, in this project, kinetic and kinematic analyses on the effects of load carriage while wearing high-heeled shoes on ankle joint during level and uphill walking will be done.

1.4 Aim and Objectives

This project aims to determine the biomechanics effects on ankle joint by varying the weight of load carriage, the heel height of the high-heeled shoes and the level of slope while walking.

The first objective of this project is to determine the kinetic and kinematic impact of load carriage to the ankle joint in walking gait. The next objective is to determine the effect of heel height to the ankle joint and the final objective is to determine the effect of incline slope to the ankle joint.

1.5 Scope and Limitation of the Study

The treadmill used while carrying out the experiment is the H/P Cosmos Instrumented Treadmill embedded with force plate. This type of treadmill used to record the ground reaction forces acted on the foot. In this study, moment force in the ankle joint is the major element that need to be discussed and the ground reaction forces collected from the treadmill provides limited source in interpreting the moment force. Thus, in order to overcome this limitation, the unknown variables have to be computed and calculated according to the constructed free body diagram. The values of variables and unknowns can be either obtained by Kinovea software, measurement or calculation. In addition, three-dimensional (3D) inputs from the force platform are needed to perform the inverse dynamics in determining the moment of joint. However, the treadmill used can only provide vertical ground reaction force (VGRF). Thus, only VGRF was considered in the calculation of joint reaction force and joint moment, without taking horizontal ground reaction force into consideration.

NPD, a market research firm, found that sales of women's backpacks were up to 28% in the past year while the sales of women's handbags had dropped gradually (Olga Khazan, 2019). It is interested to know the effects of backpack load carriage on ankle joint and thus only backpack load carriage is considered in this study and other types of load carriage are not discussed. Therefore, this study is benefit to those who are interested in the effect of backpack load carriage to the ankle joint. Just like the load carriage, the heel height considered in this study is also just 2.5 inches, instead of other heights. Thus, the results do not investigate the effect of other heel heights that affect the different moment force acted on the ankle joint.

Besides, this study only focuses on young female adults in local university with age group within 18 to 25 years old as outsiders are not allowed to enter the laboratory for experiment. This age group of 18 to 25 years old might produce different results in compared to other studies with different age group. Subjects from wider age group and different ethnicity should be considered to avoid bias on the demographic issues in different ethnics (Gefen, et al., 2002; Mari and Hiroki, 2011; Nwankwo and Egwuonwu, 2012).

Furthermore, the motion analysis of the study is recorded using camera with tripod stand. The starting time of the recorded video in the Kinovea software is not sync with the starting time of the collected data in the Kistler Gaitway Software. Therefore, a sound that indicates the starting time of collecting data in the recorded video will be produced in order to determine the actual starting time of data collection in the software.

1.6 Contribution of the Study

The kinetic and kinematic impacts caused to the ankle joint during walking with different shoe, load and slope condition were investigated in this study, such as VGRF, ankle joint force, Achilles tendon force, cadence, stride length and step length. The statistical t-test analysis on the kinetic and kinematic parameters across different condition of the shoe, load and slope can show more impacts that might cause to the ankle joint.

1.7 Outline of the Report

This report consists of five chapters.

Chapter 1 discusses the Introduction for this study, which consists of background introduction, importance of study, problem statement, aim and objectives, limitation and scope, and contribution of study.

Chapter 2 discusses the Literature Review that is related to this study. Literature Review separated into kinetic and kinematic analysis. Kinetic analysis part consists of inverse dynamic, ground reaction force and ankle moment force. On the other hand, kinematic analysis part consists of walking gait, cadence, step length and stride length.

Chapter 3 shows the Methodology and Work Plan of the study. The experiment protocol is presented in this section, and mathematical models based on the inverse dynamic method is showed to determine the ankle joint force and the angle of force acting on the ankle joint of the subject in different condition while wearing high-heeled shoes with back pack load.

Chapter 4 includes the Results and Discussion of the study. All the results shown were normalized and tabulated in tables before statistical test.

Lastly, conclusion and recommendations for future works are discussed in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the olden days, walking in high-heeled shoes has been judged passively as it is detrimental to the lower extremities and lower limb posture of women. It is viewed generally that high-heeled shoes will alter the gait pattern and the biomechanics of lower extremities. Previous research has shown that walking in high-heeled shoes was aesthetically accepted for its visualization rather than the actual functional purposes as they increases the femininity of gait where women has shorter stride lengths compared to men and increased rotation and tilt of the hips (Fath, Jurek and Secoy, 2016).

Kinetic and kinematic analyses are important factors in studying human gait and posture as they can help in analysing the effects of outer stimuli to the body joints. Both analyses will be discussed in the sub-sections below.

2.2 Kinetic Analysis

Kinetic analysis showed the results and causes which were related to the force reacted onto the human body while in motion.

2.2.1 Inverse Dynamic

Inverse dynamic is an inverse problem where it normally refers to either the inverse structural dynamics or the inverse rigid body dynamics. In other words, it is a process by working back from the kinematics and is used to derive the moments and kinetics at every joint for that particular motion. It computes forces or moments of force such as torques by referring to the kinematics, motion and the inertial properties of a body. It commonly uses link-segment models in representing the mechanical behaviour and mathematical model behaviour of the interconnected segments of the body. By constructing link-segment models, forces acted on the lower extremities can be easily seen and calculated for further analysis. Figure 2.1 below shows the example of a link-segment model.

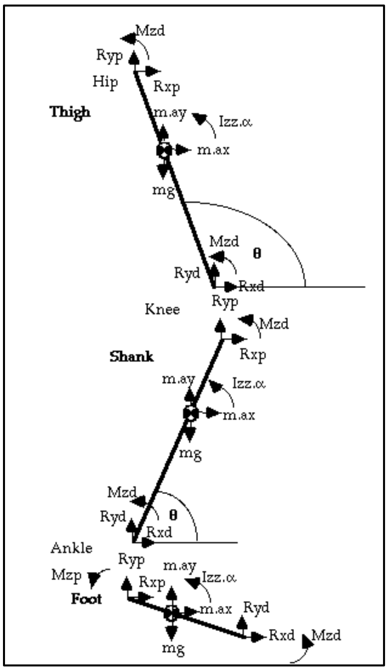

Figure 2.1: Link-segment model (Winter, 1991).

Inverse kinematics is similar to the inverse dynamic but it has different goals and starting assumptions. It is used in synthesizing the appearance of human motion, mostly in the video game design field and robotics field. Inverse dynamics are interested in finding torques produced in a certain motion and velocities, while inverse kinematics are used to find a static set of joint angles of a character positioned at a designated location.

However, there are some limitations in using inverse dynamic. It somehow depends on some assumptions that are not always valid such as the present of friction at joints. Besides, it also estimates that the joint center of rotation is prone to error (Holden and Stanhope, 1998). The typical models used by Helen Hayes rely massively on the anthropometry in defining the hip joint center where it is so deep and cannot be directly defined by markers. During motions especially at the knee, the center of rotation of the joints often move which might cause more errors while interpreting the data. Moreover, there is also some measurement errors occurred while using inverse dynamic (Holden, et al., 1997). Due to interpolation of missing markers, the marker tracking will be contaminated by errors which will make the data from some frames to be lost.

2.2.2 Ground Reaction Force and Ankle Joint Moment

In biomechanics, ground reaction force (GRF) is meant by the force exerted on a body with the ground in contact with it. For instance, a subject stands on the ground in motionless will exert a contact force on it in equal to its weight and at the same time, an equal opposite ground reaction force will be exerted back to the subject by the ground.

In the study of Kalyan (2014), it shows that the vertical ground reaction force (VGRF) and torque acted on the ankle joint were significantly greater in high-heeled shoes in compared with barefoot. While this study is supported in the study of Fath, Jurek and Secoy (2016), where it showed the VGRF at the initial contact were significantly greater in high-heeled shoes compared to in barefoot. In barefoot static standing, the weight shifting primarily occurs through the rear foot while in high-heeled shoes are through the fore foot. The increment of heel height had induced a higher ground reaction force. As reversed torque was acted on the ankle joint, the acceleration of ankle joint occurs.

In the study of Dames and Smith (2016), it showed that load carriage will increase the stance and double support times. Spatiotemporal of walking in barefoot decrease the GRF, but in turn it increases the knee and hip kinetic forces during over ground walking. In this study, regardless of the footwear chosen, larger GRF will be produced if the load carriage is higher. In terms of the backpack loads, it is suggested that the weight of load should be restricted to no more than 15% of the body weight as more than that percentage will cause muscle fatigue easily to the subjects (Hong, Li and Fong, 2008).

In the study of Burdett (1982), it showed that the ankle joint complex bears a force of approximately five times body weight during stance in normal walking, and up to thirteen times body weight during activities such as running. In the study of Brockett and Chapman (2016), they demonstrated the ankle moment obtained from gait analysis shows a dorsiflexion moment at heel strike as the dorsiflexors contracted to control the rotation of the foot onto the ground to avoid the foot from slapping the ground, as shown in Figure 2.2 below. Next, during the second phase, plantar flexor moment happened as the ankle dorsiflexors contracted in order to let forward progression of the shank over the foot. As for the third phase, there is a plantar flexion moment as the plantar flexors contracted towards the toe-off position. The ankle kinetic order is almost identical in profile but magnitudes are greater as the walking speed increases. However, ankle joint moments acquired from the gait analysis do not commonly report ankle moments in the coronal or transverse planes due to the complex nature of movement of the ankle joint complex and the high variability between individuals.

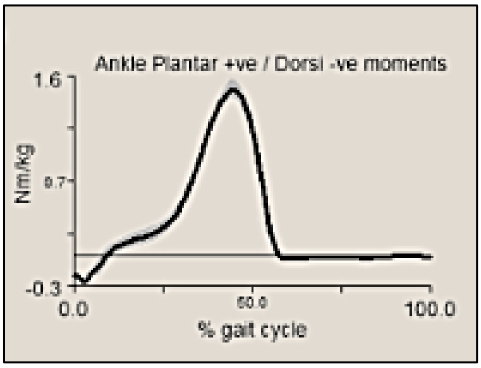

Figure 2.2: Sagittal Plane Ankle Moments (Brockett and Chapman, 2016).

Lee, Yoon and Shin (2017) proposed that uphill walking can be considered as a challenging task in daily life. For instance, one of the most popular recreational activities is hiking (Bohne and Abendroth-Smith, 2007). There is a transition between level and uphill walking where there will be some modification in walking strategy (Prentice, et al., 2004; Minetti, Ardigo and Saibene, 1993). The biomechanics of the lower extremities are different in uphill walking compared to that of level walking where more work is completed by the leg muscles during uphill walking (McIntosh, et al., 2006). In uphill walking, the ankle extensor muscles performed great positive work so that the COM is rose during uphill walking (Franz, Lyddon and Kram, 2012). Thus, uphill walking can cause musculoskeletal pain and injuries to the body (Blake and Ferguson, 1993).

2.3 Kinematic Analysis

Kinematic analysis measures the kinematic quantities used to describe motion of a subject.

2.3.1 Walking Gait

Walking seems to be an uncomplicated activity. Nevertheless, there are many systems of the body that work together in order to make a subject walk in a normal gait. Gait can be defined as the process of legs in a motion while loading and unloading weight (Mirelman, et al., 2018). The assessment of gait can help in estimating the overall health status (Fritz and Lusardi, 2009; Middleton, Fritz and Lusardi, 2015).

Heel strike, stance phase and toe-off are consisted in a normal gait cycle. When the foot is in contact with the ground, it is referring the stance phase; when the foot is off the ground, it is referring the swing phase. According to Fitzpatrick (2014), during a normal gait, the knee extends till the lower extremities swings forward with foot flexed and raised upward from the ground, which is known as dorsal flexion, as shown in Figure 2.3 below. Then, the leg is extended and the body of subject moves forward, forming a heel strike followed by an extension of foot which is known as plantar flexion as the foot is on the ground. The following phase is the toe-off where the heel of the foot started to raise during the push-off of the entire gait.

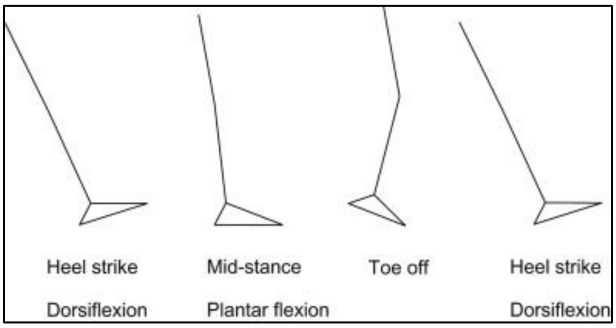

Figure 2.3: Dorsiflexion and Plantar Flexion Phases of Gait (Fitzpatrick, 2014).

2.3.2 Cadence, Step Length and Stride Length

Cadence, step length and stride length can be easily detected via the motion analysis system and are important in analysing the alteration of kinematic parameters. Cadence is expressed in steps per minute. As shown in Figure 2.4 below, step length is the distance between the heel contact point of one foot and the other foot, while stride length is the distance between successive heel contact points of the same foot (Modustrex, 2015). Two times of step length is equal to one time of stride length.

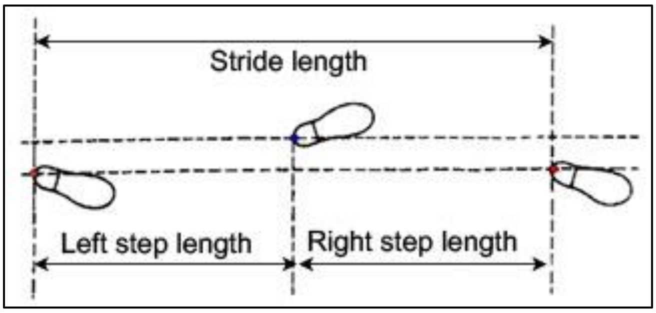

Figure 2.4: Step Length and Stride Length (Modustrex, 2015).

In the study of Lee (2014), it was found that during heel strike, foot flat, midstance and toe-off, there was a significant amount of increment in the angle of ankle joint. In the study of Chow, et al. (2005), it said that with increasing of backpack load, the walking speed and cadence decreased significantly. They also suggested that a critical load is to be approximately around 10% of the body weight. This can be supported by the study of Lee, Yoon and Shin (2017), where it reported that the stance time decreased significantly with backpack carriage. It was indicated that increasing in walking speed with a heavy backpack might be a compensatory mechanism in reducing the instability of the body during uphill walking.

2.4 Summary

Researches regarding kinetic and kinematic analysis that are important in studying human gait and posture were discussed.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this project, there are to be completed which are planning, pre-testing of experiment, recruitment of subjects, experiment protocol, data collection and data processing and analysis. Each phase plays an important role in order to ensure precise and accurate data can be collected. The overall process flow is clearly shown in Figure 3.1 below.

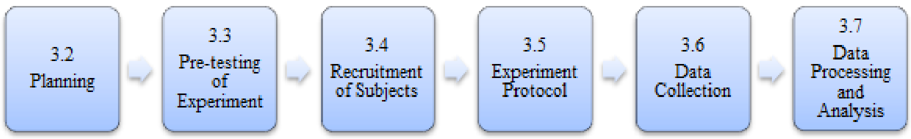

Figure 3.1: Progress Flow.

3.2 Planning

There were four important parameters that need to be considered while planning the entire experiment flow, which were the characteristics of high-heeled shoes, the weight of load, the walking speed of subjects, the time interval of data collection and the incline slope selection.

3.2.1 Characteristics of High-Heeled Shoes

A pin-pointed high-heeled shoe with the heel length of 0.0635 m and the tip base diameter of 1 cm is used in the study, as shown in Figure 3.2. In order to standardize the data for future analysis and studies, the size of the high-heeled shoe was set at size UK7 which is the most common foot size for women.

Barefoot was the control variable of the study. Previous studies have shown that wearing high-heeled shoes occasionally will eventually decrease the pronation of the foot during the support phase of walking (Cronin, Barrett and Carty, 2012). Barefoot walking and walking in shoe shows difference in their walking mechanics (Dames and Smith, 2016).

Figure 3.2: High-Heeled Shoe used for Study.

3.2.2 Weight of Load

NPD, a market research firm, found that sales of women's backpacks were up to 28% in the past year while the sales of women's handbags had dropped gradually (Olga Khazan, 2019). Based on significant changes in the physical performance, interests regarding the effects of load carriage have led to suggestions and recommendations that backpacks are to be limited within 10% to 15% of body weight (Chow, et al., 2005). Studies have suggested that the critical mass that might change and alter the walking gait and posture while producing significant effects on subjects when carrying load is 10% of the body mass (Lee and Li, 2014). Thus, 10% of the body mass has been set as the weight of load in this study. Zero weight of load was the control variable of the study in order to demonstrate the difference.

3.2.3 Walking Speed of Subjects

According to the previous studies, some might have self-selected speed while some might have pre-set or controlled speed for subjects to walk on the treadmill. Pre-testing on the treadmill had been done before the experiment was started and subjects revealed that self-selected speed is more suitable for them as they might have the risk of falling down if they walked using the pre-set speed.

Self-selected speed will provide natural walking gait to the subjects and it was close to the most efficient walking pattern (Cronin, 2014). Pre-set speed will restrict the walking pattern of the subjects which will alter the posture while producing significant effects on the subjects. Thus, self-selected speed for subjects to walk on the treadmill has been decided in this study.

3.2.4 Time Interval of Data Collection

According to previous study, the time used to collect data during walking was controlled at 30 seconds for each trial (Ho, et al., 2010). Pre-testing on the treadmill has been done and subjects revealed that if the trial duration was too long, they might feel fatigue as they need to walk continuously in different condition. However, shorter time duration was also tested and it showed that the data recorded was not sufficient for data analysis.

After a few testing, 30 seconds for each trial was set as the duration for each trial in this study as this duration provides sufficient data for data analysis and subjects feel comfortable throughout the whole experiment. Sufficient break time will also be provided after a few conditions in order to ensure subjects do not feel fatigue easily while experiment was carried out.

3.2.5 Incline Slope Selection

Previous study has chosen 15% slope as the condition in their research (Grampp, Willson and Kernozek, 2000; Sabatini, et al., 2004). After a few tried and tested, subjects revealed that they feel extremely tired and muscle fatigue even though they just tried for one condition. Another trial was conducted by reducing the percentage to 10% as shown in another study (Vogt and Banzer, 1999; Ferley, Osborn and Vukovich, 2013). Subjects feel more comfortable and prefer this slope than the previous one. By summarizing all the studies above, 10% incline slope selection was used in this study. The degree of incline slope can be calculated using the Equation 3.1 below (Ferley, Osborn and Vukovich, 2013).

$$Degree = \tan^{-1}\left(\frac{Slope\ Percentage}{100}\right) \tag{3.1}$$

3.3 Pre-Testing of Experiment

Pre-testing of experiment was done to ensure that all the parameters and conditions were clearly selected and suitable for the study to achieve the aim and objectives of this project. Two subjects were required to walk on the treadmill embedded with force plate with barefoot and the prepared high-heeled shoes.

Before the pre-testing was started, a simple briefing will be done on how the entire experiment runs to ensure the subjects understand their role. They select their own preferable speed to walk on the treadmill. Few conditions will be considered while they were walking on the treadmill, which are barefoot unloaded, high-heeled shod unloaded, barefoot loaded, shod loaded. Level and uphill (incline) walking will also be considered within the pre-testing sessions. After the trials, the subjects commented that the heel height, weight of load, time interval and the incline slope were acceptable.

3.4 Recruitment of Subjects

The target population in this project is volunteer young healthy local university female undergraduates with foot sized of UK7 which are aged within 18 to 25 years old. Besides, the subjects recruited must have normal body mass index (BMI) as it will affect the force distribution at the foot and provide different gait parameters (Yan, et al., 2013). Subjects should also be free from postural deformities, for instance flat foot and high arch. Besides, subjects should also be free from orthopaedic problems or any lower extremities diseases to avoid any happening of accidents.

3.5 Experiment Protocol

Figure 3.3 below shows the experiment protocol of this project. There were eight conditions that need to be completed, where each condition needs to be repeated thrice in order to get an average outcome. Sticker markers were placed on the coordinate of ankle joint, knee joint, heel and toe of the subject. Break time within trials will be provided to ensure the subjects to not feel fatigue easily while the experiment was carried out.

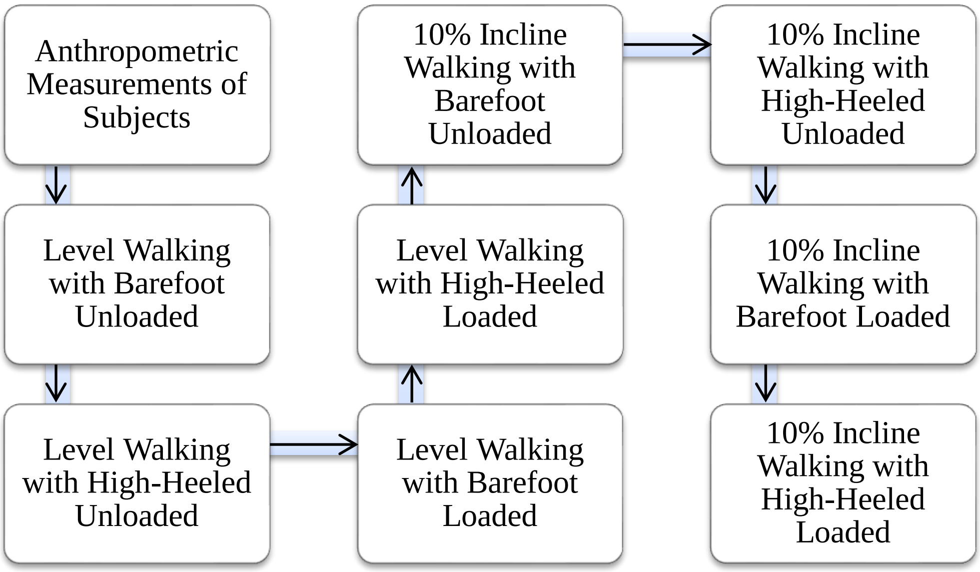

Figure 3.3: Experiment Protocol.

3.6 Data Collection

Anthropometric and gait data measurements were collected in the experiment for future analysis for this project.

3.6.1 Anthropometric Measurement of Subjects

Table 3.1 below shows various anthropometric data that need to be measured from subjects. All of the measurements can be easily got by using a measuring tape and all of them were useful in calculating the moment force. Figure 3.4 to figure 3.6 below shows the examples of measurement of parameters.

Table 3.1: Anthropometric Measurement.

Parameters	Data
Name	
Age	
Body Height (cm)	
Body Mass (kg)	
Heel Height, *a* (cm)	
Length of Heel to Ankle, *b* (cm)	
Foot Length, *c* (cm)	
Length of Heel Tip to Ankle in horizontal direction, *e* (cm)	
Length of Heel Tip to Ankle in vertical direction, *i* (cm)	
Leg Length, l_o (cm)	
Angle between High-Heeled Shoes and Inclined Plane, σ (°)	

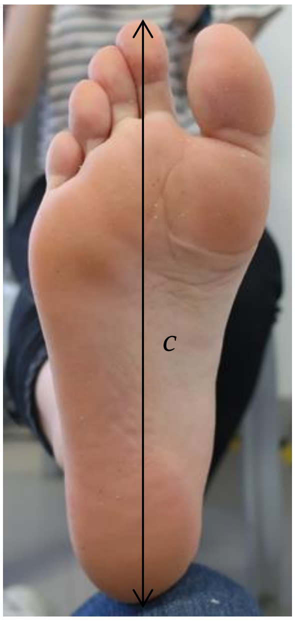

Figure 3.4: Foot Length, *c*.

Figure 3.5: Heel Height, *a* and Length of Heel to Ankle, *b*.

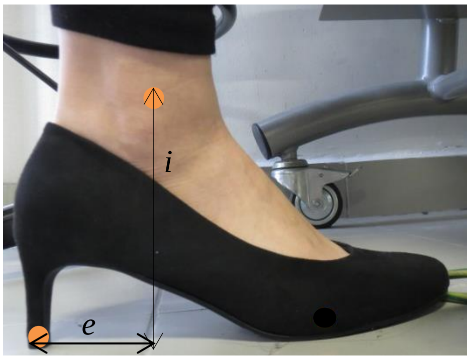

Figure 3.6: Length of Heel Tip to Ankle in horizontal direction, *e* and Length of Heel Tip to Ankle in vertical direction, *i* (cm).

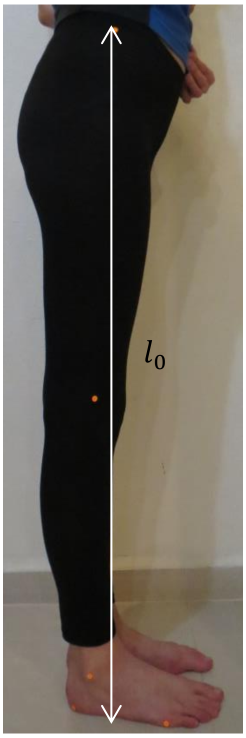

Figure 3.7: Leg Length, l_o.

3.6.2 Gait Data

H/P Cosmos Instrumented Treadmill (Model: TLA10004681) embedded with force plate was used to retrieve gait data while subjects walked on it. Kistler Gaitway Software was used for gait data collection. The gait data were extracted and used for further analysis. Measuring tape was used for measuring and recording the anthropometric data of subjects.

3.7 Data Processing and Analysis

The gait data from the Kistler Gaitway Software was extracted and used for kinetic measurements. Then, anthropometric measurements and the extracted gait data were used to calculate the kinetic and kinematic data of the lower extremities.

3.7.1 Data Extraction and Normalization

Gait data was extracted from the Kistler Gaitway Software. Kinovea software was also used in determining the angle between various joints on the leg. Sticker marker was put on the specific joint in order to visualize the joints on Kinovea software. Data normalization is a process for reducing variation of the database (Bolstad, et al., 2003) and improves data integrity to reach a linear relationship. According to Hof (1996), it is important to make use of normalization to reduce the unavoidable inter-individual differences to correct the unequal anthropometric parameters of the recruited subjects. Table 3.2 below shows some of the formula used to perform the data normalization.

Table 3.2: Equations for Data Normalization.

Parameters	Dimensionless Number
Step Length/ Stride Length, $l_{step/stride}$	$\acute{l}_{step/stride} = \frac{l}{l_0}$ (3.2)
Cadence, c	$\hat{c} = \frac{c}{60\sqrt{g/l_0}}$ (3.3)
VGRF, F	$\hat{F} = \frac{F}{m_{body} \times g}$ (3.4)
Achilles Tendon Force, F_{AT}	$\dot{F_{AT}} = \frac{F_{AT}}{mass_{body} \times g}$ (3.5)
Ankle Joint Force, A	$\dot{A} = \frac{A}{m_{body} \times g}$ (3.6)

where

$\acute{l}_{step/stride}$= Normalized Step Length and Stride Length

$\hat{c}$ = Normalized Cadence

$\hat{F}$ = Normalized VGRF

$\dot{F_{AT}}$ = Normalized Achilles Tendon Force

$\dot{A}$ = Normalized Ankle Joint Force

3.8 Free Body Diagram and Sample Calculation

Subsection below shows the free body diagram and mathematical modelling for the models in different condition. Sample calculations for different condition were also shown in the following subsection.

3.8.1 Level Barefoot Model

Figure 3.8 below shows the constructed free body diagram. Forces were acting onto the foot which were the vertical ground reaction force (VGRF), Achilles Tendon Force (F_{AT}) and ankle joint force (A). According to the free body diagram, there were variables and unknowns that need to be find out. The values of variables and unknowns can be either obtained by Kinovea software, measurement or calculation. Table 3.3 below shows the categorical of the variables and unknowns.

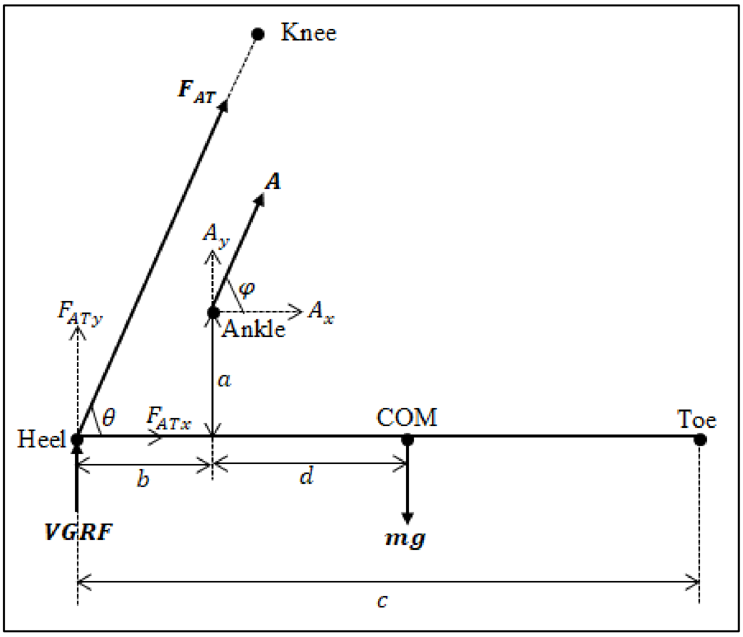

Figure 3.8: Free Body Diagram for Level Barefoot Model.

Table 3.3: Categorical of Unknowns for Level Barefoot Model.

Categories	Unknown	Definition
By Kinovea software	θ	Achilles tendon force angle
By Measurement	a	Heel height
	b	Length of heel to ankle
	c	Foot Length
By Calculation	d	Length of ankle to COM
	m	Segmental mass of foot
	F_{AT}	Achilles tendon force

where

COM = center of mass

3.8.1.1 Sample Calculation for Level Barefoot Model

By referring to the free body diagram shown in Figure 3.8 above, Equation 3.7 to Equation 3.9 below show the calculation of the calculated unknowns.

The length of ankle to COM, *d* can be calculated using the equation 3.7 below:

$$d = \frac{c}{2} - b \tag{3.7}$$

where
b = length of heel to ankle, *cm*
c = foot length, *cm*

According to M. Dempster (1973), the center of mass (COM) of the foot is 50% of the foot length.

$$COM = 50\% \times c \tag{3.8}$$

where
c = foot length, *cm*

According to M. Dempster (1973), the segmental mass of foot can be calculated using Equation 3.9 below.

$$m = 1.45\% \times m_{body} \tag{3.9}$$

where
m = segmental mass of foot, *kg*
m_{body} = body mass, *kg*

After obtaining all the unknown variables shown in the free body diagram, ankle joint force and ankle joint moment force have been calculated as shown in Equation 3.10 to Equation 3.14 below.

$$\sum M_{ankle} = 0 \tag{3.10}$$
$$\sum M_{cc} + \sum M_c = 0$$
$$\left[(VGRF \times b) + \left(F_{ATy} \times b\right) + (mg \times d)\right] + [-(F_{ATx} \times a)] = 0$$
$$[(VGRF \times b) + (F_{AT} \sin\theta \times b) + (mg \times d)] + [-(F_{AT} \cos\theta \times a)] = 0$$
$$bF_{AT} \sin\theta - aF_{AT} \cos\theta = -[(VGRF \times b) + (mg \times d)]$$
$$F_{AT}(b \sin\theta - a \cos\theta) = -[(VGRF \times b) + (mg \times d)]$$
$$F_{AT} = \frac{-[(VGRF \times b) + (mg \times d)]}{(b \sin\theta - a \cos\theta)}$$

where

M_{ankle} = ankle moment, *N m*

M_{cc} = counter-clockwise moment, *N m*

M_c = clockwise moment, *N m*

$VGRF$ = vertical ground reaction force, *N*

b = length of heel to ankle, *m*

mg = COM, $kgms^{-1}$

d = length of ankle to COM, *m*

F_{AT} = Achilles tendon force, *N*

a = heel height, *m*

Total horizontal force can be calculated using Equation 3.11 below.

$$\rightarrow + \sum F_x = 0 \tag{3.11}$$
$$F_{ATx} + A_x = 0$$
$$F_{AT} \cos\theta + A_x = 0$$
$$A_x = -F_{AT} \cos\theta$$

where

F_{ATx} = horizontal Achilles tendon force, *N*

A_x = horizontal ankle joint force, *N*

Total vertical force can be calculated using Equation 3.12 below.

$$\uparrow + \sum F_y = 0 \tag{3.12}$$
$$F_{ATy} - mg + VGRF + A_y = 0$$
$$F_{AT}\sin\theta - mg + VGRF + A_y = 0$$
$$A_y = -F_{AT}\sin\theta + mg - VGRF$$

where

F_{ATy} = vertical Achilles tendon force, *N*

A_y = vertical ankle joint force, *N*

mg = COM, $kgms^{-1}$

$VGRF$ = vertical ground reaction force, *N*

Net ankle joint force, *A* can be calculated using Equation 3.13 below.

$$A = \sqrt{{A_x}^2 + {A_y}^2} \tag{3.13}$$

where

A_x = horizontal ankle joint force, *N*

A_y = vertical ankle joint force, *N*

Angle of action of ankle joint force, φ can be calculated using Equation 3.14 below.

$$\varphi = \tan^{-1}\frac{A_y}{A_x} \tag{3.14}$$

where

A_x = horizontal ankle joint force, N

A_y = vertical ankle joint force, N

3.8.1.2 Performance of Sample Calculation for Level Barefoot Model

Performed sample calculation was shown below by using the sample calculation steps as shown in subsection 3.8.1.1.

Length of ankle to COM, *d*:

$$d = \frac{c}{2} - b$$
$$= \frac{0.23}{2} - 0.04$$
$$= 0.075\ m$$

COM:

$$COM = 50\% \times c$$
$$= 50\% \times 0.23$$
$$= 0.115\ m$$

Segmental mass of foot, *m*:

$$m = 1.45\% \times m_{body}$$
$$= 1.45\% \times 49.05$$
$$= 0.7112\ kg$$

Archilles tendon force, F_{AT}:

$$F_{AT} = \frac{-[(VGRF \times b) + (mg \times d)]}{(b \sin\theta - a \cos\theta)}$$
$$= \frac{-[(523.566 \times 0.04) + (0.7112 \times 9.81 \times 0.075)]}{(0.04 \sin 89° - 0.07 \cos 89°)}$$
$$= -553.642\ N$$

Horizontal ankle joint force, A_x:

$$A_x = -F_{AT} \cos\theta$$
$$= -(-553.642)(\cos 89°)$$
$$= 9.6624 \text{ N}$$

Vertical ankle joint force, A_y:

$$A_y = -F_{AT} \sin\theta + mg - VGRF$$
$$= -(-553.642)(\sin 89°) + (0.7112 \times 9.81) - 523.566$$
$$= 36.9684\ N$$

Net ankle joint force, A:

$$A = \sqrt{{A_x}^2 + {A_y}^2}$$

$$= \sqrt{(9.6624)^2 + (36.9684)^2}$$

$$= 38.2102 \text{ N}$$

Angle of action of ankle joint force, φ:

$$\varphi = \tan^{-1}\frac{A_y}{A_x}$$

$$= \tan^{-1}\frac{36.9684}{9.6624}$$

$$= 75.35°$$

3.8.2 Level High-Heeled Model

Figure 3.9 below shows the constructed free body diagram. Forces were acting onto the foot which were the vertical ground reaction force (VGRF), Achilles Tendon Force (F_{AT}) and ankle joint force (A). According to the free body diagram, there were variables and unknowns that need to be find out. The values of variables and unknowns can be either obtained by Kinovea software, measurement or calculation. Table 3.4 below shows the categorical of the variables and unknowns.

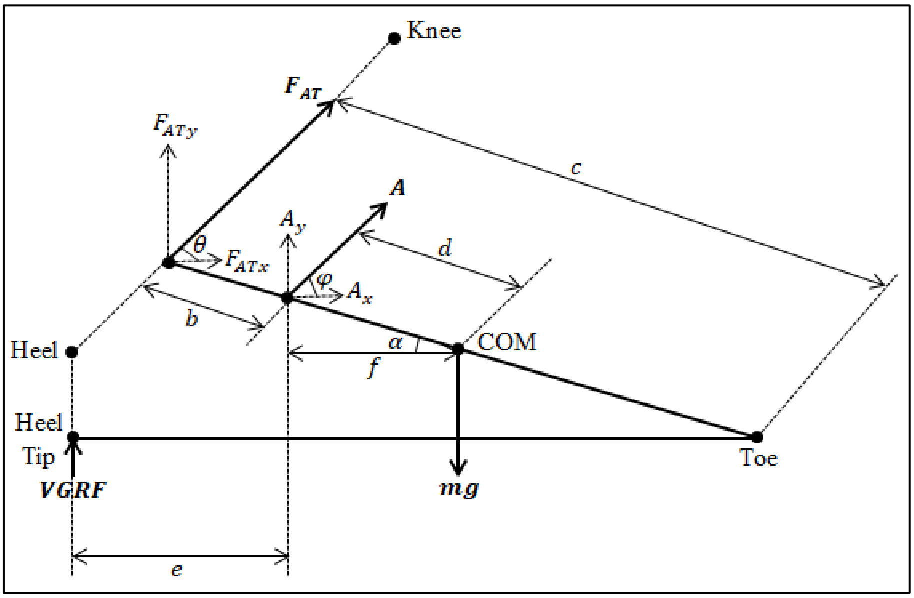

Figure 3.9: Free Body Diagram for Level High-Heeled Model.

Table 3.4: Categorical of Unknowns for Level High-Heeled Model.

Categories	Unknown	Definition
By Kinovea software	θ	Achilles tendon force angle
	α	Ankle, COM and heel angle
By Measurement	b	Length of heel to ankle
	c	Foot Length
	e	Length of heel tip and ankle
By Calculation	d	Length of ankle to COM
	f	Moment arm of COM
	m	Segmental mass of foot
	F_{AT}	Achilles tendon force

where

COM = center of mass

3.8.2.1 Sample Calculation for Level High-Heeled Model

By referring to the free body diagram shown in Figure 3.9 above, Equation 3.15 to Equation 3.18 below show the calculation of the calculated unknowns.

The length of ankle to COM, *d* can be calculated using equation 3.15 below:

$$d = \frac{c}{2} - b \tag{3.15}$$

where

b = length of heel to ankle, *cm*

c = foot length, *cm*

The moment arm of COM, *f* can be calculated using equation 3.16 below:

$$f = d \cos \alpha \tag{3.16}$$

where

d = length of ankle to COM, *m*

α = ankle, COM and heel ankle, °

According to M. Dempster (1973), the center of mass (COM) of the foot is 50% of the foot length.

$$COM = 50\% \times c \tag{3.17}$$

where

c = foot length, *cm*

According to M. Dempster (1973), the segmental mass of foot can be calculated using Equation 3.18 below.

$$m = 1.45\% \times m_{body} \tag{3.18}$$

where

m = segmental mass of foot, *kg*

m_{body} = body mass, *kg*

After obtaining all the unknown variables shown in the free body diagram, ankle joint force and ankle joint moment force have been calculated as shown in Equation 3.19 to Equation 3.18 below.

$$\sum M_{ankle} = 0 \tag{3.19}$$
$$\sum M_{cc} = 0$$
$$(VGRF \times e) + (F_{AT} \times b) + (mg \times f) = 0$$
$$F_{AT} = \frac{-[(VGRF \times e) + (mg \times f)]}{b}$$

where

M_{ankle} = ankle moment, *N m*

M_{cc} = counter-clockwise moment, *N m*

$VGRF$ = vertical ground reaction force, *N*

e = length of heel tip to ankle, *m*

mg = COM, *kgms*$^{-1}$

f = moment arm of COM, *m*

F_{AT} = Achilles tendon force, *N*

b = length of heel to ankle, *m*

Total horizontal force can be calculated using Equation 3.20 below.

$$\rightarrow + \sum F_x = 0 \tag{3.20}$$
$$F_{ATx} + A_x = 0$$
$$F_{AT} \cos\theta + A_x = 0$$
$$A_x = -F_{AT} \cos\theta$$

where

F_{ATx} = horizontal Achilles tendon force, *N*

A_x = horizontal ankle joint force, *N*

Total vertical force can be calculated using Equation 3.21 below.

$$\uparrow + \sum F_y = 0 \tag{3.21}$$
$$F_{ATy} - mg + VGRF + A_y = 0$$
$$F_{AT} \sin\theta - mg + VGRF + A_y = 0$$
$$A_y = -F_{AT} \sin\theta + mg - VGRF$$

where

F_{ATy} = vertical Achilles tendon force, *N*

A_y = vertical ankle joint force, *N*

mg = COM, $kgms^{-1}$

$VGRF$ = vertical ground reaction force, *N*

Net ankle joint force, *A* can be calculated using Equation 3.22 below.

$$A = \sqrt{{A_x}^2 + {A_y}^2} \tag{3.22}$$

where

A_x = horizontal ankle joint force, N

A_y = vertical ankle joint force, N

Angle of action of ankle joint force, φ can be calculated using Equation 3.23 below.

$$\varphi = \tan^{-1}\frac{A_y}{A_x} \tag{3.23}$$

where

A_x = horizontal ankle joint force, N

A_y = vertical ankle joint force, N

3.8.2.2 Performance of Sample Calculation for Level High-Heeled Model

Performed sample calculation was shown below by using the sample calculation steps as shown in subsection 3.8.2.1.

Length of ankle to COM, *d*:

$$\begin{aligned} d &= \frac{c}{2} - b \\ &= \frac{0.23}{2} - 0.04 \\ &= 0.075\, m \end{aligned}$$

Moment arm of COM, *f*:

$$\begin{aligned} f &= d\cos\alpha \\ &= 0.075\cos 25° \\ &= 0.0680\, m \end{aligned}$$

COM:

$$\begin{aligned} COM &= 50\% \times c \\ &= 50\% \times 0.23 \\ &= 0.115\, m \end{aligned}$$

Segmental mass of foot, m:

$$m = 1.45\% \times m_{body}$$
$$= 1.45\% \times 49.05$$
$$= 0.7112\ kg$$

Archilles tendon force, F_{AT}:

$$F_{AT} = \frac{-[(VGRF \times e) + (mg \times f)]}{b}$$
$$= \frac{-[(574.498 \times 0.05) + (0.7112 \times 9.81 \times 0.0680)]}{0.04}$$
$$= -729.979\ N$$

Horizontal ankle joint force, A_x:

$$A_x = -F_{AT}\ \cos\theta$$
$$= -(-729.979)(\cos 88°)$$
$$= 25.476\ \mathrm{N}$$

Vertical ankle joint force, A_y:

$$A_y = -F_{AT}\sin\theta + mg - VGRF$$
$$= -(-729.979)(\sin 88°) + (0.7112 \times 9.81) - 574.498$$
$$= 162.013\ N$$

Net ankle joint force, A:

$$A = \sqrt{{A_x}^2 + {A_y}^2}$$
$$= \sqrt{(25.476)^2 + (162.013)^2}$$
$$= 164.004\ \mathrm{N}$$

Angle of action of ankle joint force, φ:

$$\varphi = \tan^{-1}\frac{A_y}{A_x}$$
$$= \tan^{-1}\frac{162.013}{25.476}$$
$$= 81.06°$$

3.8.3 Inclined Barefoot Model

Figure 3.10 below shows the constructed free body diagram. Forces were acting onto the foot which were the vertical ground reaction force (VGRF), Achilles Tendon Force (F_{AT}) and ankle joint force (A). According to the free body diagram, there were variables and unknowns that need to be find out. The values of variables and unknowns can be either obtained by Kinovea software, measurement or calculation. Table 3.5 below shows the categorical of the variables and unknowns.

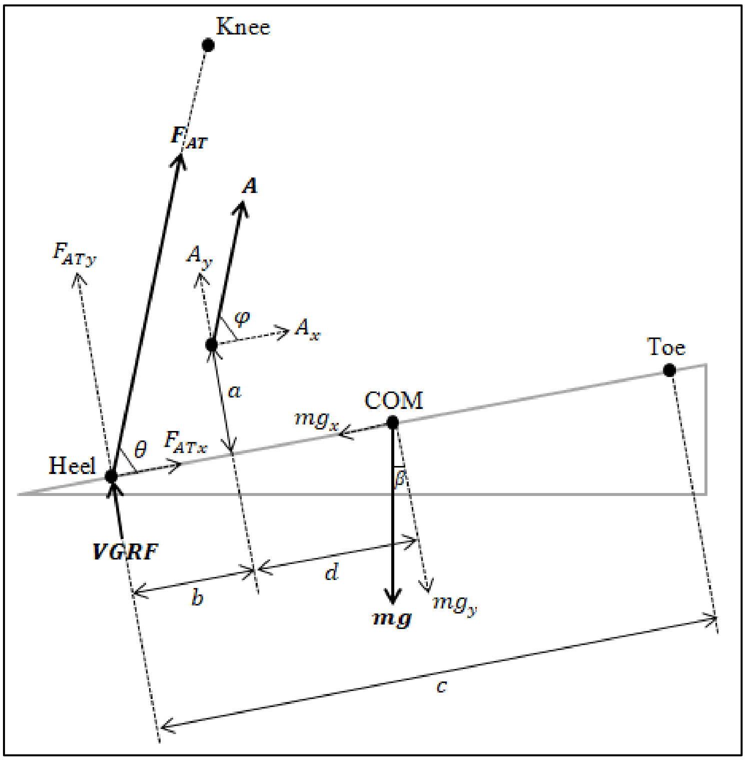

Figure 3.10: Free Body Diagram for Level Barefoot Model.

Table 3.5: Categorical of Unknowns for Inclined Barefoot Model.

Categories	Unknown	Definition
By Kinovea software	θ	Achilles tendon force angle
	β	Angle of elevation
By Measurement	a	Heel height
	b	Length of heel to ankle
	c	Foot Length
By Calculation	d	Length of ankle to COM
	m	Segmental mass of foot

Table 3.5 (Continued)

	F_{AT}	Achilles tendon force

where

COM = center of mass

3.8.3.1 Sample Calculation for Inclined Barefoot Model

By referring to the free body diagram shown in Figure 3.8 above, Equation 3.24 to Equation 3.26 below show the calculation of the calculated unknowns.

The length of ankle to COM, d can be calculated using the equation 3.24 below:

$$d = \frac{c}{2} - b \tag{3.24}$$

where

b = length of heel to ankle, *cm*

c = foot length, *cm*

According to M. Dempster (1973), the center of mass (COM) of the foot is 50% of the foot length.

$$COM = 50\% \times c \tag{3.25}$$

where

c = foot length, *cm*

According to M. Dempster (1973), the segmental mass of foot can be calculated using Equation 3.26 below.

$$m = 1.45\% \times m_{body} \tag{3.26}$$

where

m = segmental mass of foot, *kg*

m_{body} = body mass, *kg*

After obtaining all the unknown variables shown in the free body diagram, ankle joint force and ankle joint moment force have been calculated as shown in Equation 3.27 to Equation 3.31 below.

$$\sum M_{ankle} = 0 \tag{3.27}$$
$$\sum M_{cc} + \sum M_c = 0$$
$$\left[(VGRF \times b) + \left(F_{ATy} \times b\right) + (mg_x \times a) + (mg_y \times d)\right] + [-(F_{ATx} \times a)] = 0$$
$$[(VGRF \times b) + (F_{AT} \sin\theta \times b) + (mg \sin\beta \times a) + (mg \cos\beta \times d)] + [-(F_{AT} \cos\theta \times a)] = 0$$
$$bF_{AT} \sin\theta - aF_{AT} \cos\theta = -[(VGRF \times b) + (mg \sin\beta \times a) + (mg \cos\beta \times d)]$$
$$F_{AT}(b \sin\theta - a \cos\theta) = -[(VGRF \times b) + (mg \sin\beta \times a) + (mg \cos\beta \times d)]$$
$$F_{AT} = \frac{-[(VGRF \times b) + (mg \sin\beta \times a) + (mg \cos\beta \times d)]}{(b \sin\theta - a \cos\theta)}$$

where

M_{ankle} = ankle moment, *N m*

M_{cc} = counter-clockwise moment, *N m*

M_c = clockwise moment, *N m*

$VGRF$ = vertical ground reaction force, *N*

b = length of heel to ankle, *m*

mg = COM, $kgms^{-1}$

d = length of ankle to COM, *m*

F_{AT} = Achilles tendon force, *N*

a = heel height, *m*

Total horizontal force can be calculated using Equation 3.28 below.

$$\rightarrow + \sum F_x = 0 \tag{3.28}$$
$$F_{ATx} + A_x - mg_x = 0$$

$$F_{AT}\cos\theta + A_x - mg\sin\beta = 0$$
$$A_x = -F_{AT}\ \cos\theta + mg\sin\beta$$

where

F_{ATx} = horizontal Achilles tendon force, *N*

A_x = horizontal ankle joint force, *N*

Total vertical force can be calculated using Equation 3.29 below.

$$\uparrow + \sum F_y = 0 \qquad (3.29)$$
$$F_{ATy} - mg_y + VGRF + A_y = 0$$
$$F_{AT}\sin\theta - mg\cos\beta + VGRF + A_y = 0$$
$$A_y = -F_{AT}\sin\theta + mg\cos\beta - VGRF$$

where

F_{ATy} = vertical Achilles tendon force, *N*

A_y = vertical ankle joint force, *N*

mg = COM, $kgms^{-1}$

$VGRF$ = vertical ground reaction force, *N*

Net ankle joint force, *A* can be calculated using Equation 3.30 below.

$$A = \sqrt{{A_x}^2 + {A_y}^2} \qquad (3.30)$$

where

A_x = horizontal ankle joint force, *N*

A_y = vertical ankle joint force, *N*

Angle of action of ankle joint force, φ can be calculated using Equation 3.31 below.

$$\varphi = \tan^{-1}\frac{A_y}{A_x} \qquad (3.31)$$

where

A_x = horizontal ankle joint force, N

A_y = vertical ankle joint force, N

3.8.3.2 Performance of Sample Calculation for Inclined Barefoot Model

Performed sample calculation was shown below by using the sample calculation steps as shown in subsection 3.8.3.1.

Length of ankle to COM, d:

$$d = \frac{c}{2} - b$$
$$= \frac{0.23}{2} - 0.04$$
$$= 0.075\ m$$

COM:

$$COM = 50\% \times c$$
$$= 50\% \times 0.23$$
$$= 0.115\ m$$

Segmental mass of foot, m:

$$m = 1.45\% \times m_{body}$$
$$= 1.45\% \times 49.05$$
$$= 0.7112\ kg$$

Archilles tendon force, F_{AT}:

$$F_{AT} = \frac{-[(VGRF \times b) + (mg \sin\beta \times a) + (mg \cos\beta \times d)]}{(b \sin\theta - a \cos\theta)}$$

$$= \frac{-[(513.639 \times 0.04) + (6.9771 \times \sin 5° \times 0.07) + (6.9771 \times \cos 5° \times 0.075)]}{(0.04 \sin 88° - 0.07 \cos 88°)}$$

$$= -562.478\ N$$

Horizontal ankle joint force, A_x:

$$A_x = -F_{AT} \cos\theta + mg \sin\beta$$

$$= -(-562.478)(\cos 88°) + 6.9771 \sin 5°$$
$$= 20.2365 \text{ N}$$

Vertical ankle joint force, A_y:

$$A_y = -F_{AT} \sin\theta + mg\cos\beta - VGRF$$
$$= -(-562.478)(\sin 88°) + 6.9771 \cos 5° - 513.639$$
$$= 55.3968\, N$$

Net ankle joint force, A:

$$A = \sqrt{{A_x}^2 + {A_y}^2}$$
$$= \sqrt{(20.2365)^2 + (55.3968)^2}$$
$$= 58.9773\text{N}$$

Angle of action of ankle joint force, φ:

$$\varphi = \tan^{-1}\frac{A_y}{A_x}$$
$$= \tan^{-1}\frac{55.3968}{20.2365}$$
$$= 69.93°$$

3.8.4 Inclined High-Heeled Model

Figure 3.11 below shows the constructed free body diagram. Forces were acting onto the foot which were the vertical ground reaction force (VGRF), Achilles Tendon Force (F_{AT}) and ankle joint force (A). According to the free body diagram, there were variables and unknowns that need to be find out. The values of variables and unknowns can be either obtained by Kinovea software, measurement or calculation. Table 3.6 below shows the categorical of the variables and unknowns.

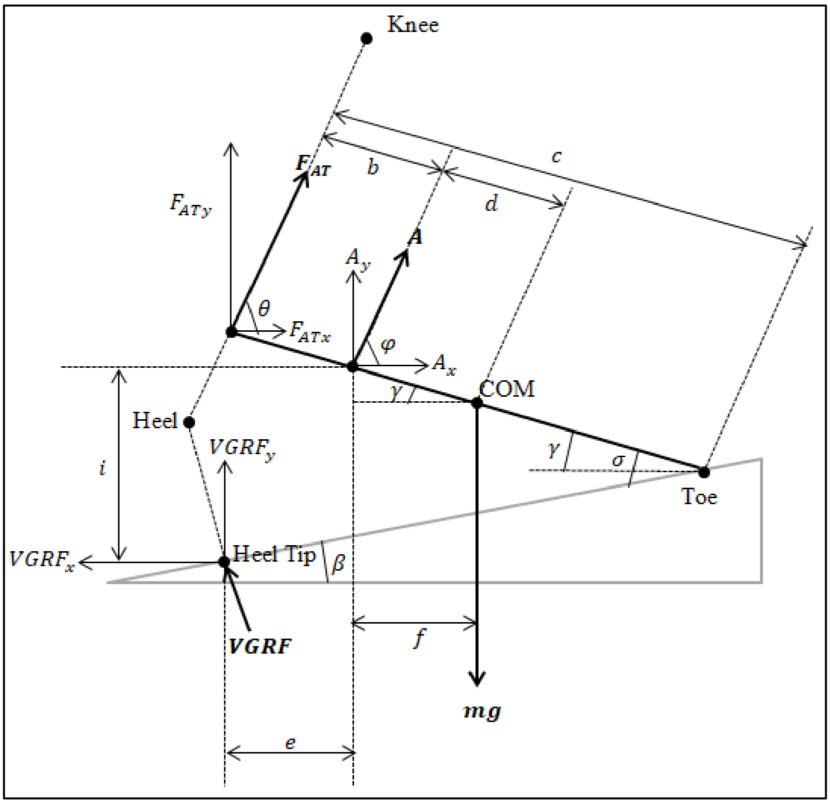

Figure 3.11: Free Body Diagram for Inclined High-Heeled Model.

Table 3.6: Categorical of Unknowns for Inclined High-Heeled Model.

Categories	Unknown	Definition
By Kinovea software	θ	Achilles tendon force angle
	β	Angle of elevation
By Measurement	a	Heel height
	b	Length of heel to ankle
	c	Foot length
	e	Length of heel tip and ankle in horizontal direction
	i	Length of heel tip and ankle in vertical direction
	σ	Angle between high-heeled shoes and inclined plane
By Calculation	d	Length of ankle to COM
	f	Moment arm of COM
	γ	Angle of COM of mg
	m	Segmental mass of foot
	F_{AT}	Achilles tendon force

where

COM = center of mass

3.8.4.1 Sample Calculation for Inclined High-Heeled Model

By referring to the free body diagram shown in Figure 3.11 above, Equation 3.32 to Equation 3.41 below show the calculation of the calculated unknowns.

The length of ankle to COM, *d* can be calculated using equation 3.32 below:

$$d = \frac{c}{2} - b \tag{3.32}$$

where

b = length of heel to ankle, *cm*

c = foot length, *cm*

The angle of COM of mg can be calculated using equation 3.33 below:

$$\gamma = \sigma - \beta \tag{3.33}$$

where

σ = angle between high-heeled shoes and inclined plane, °

β = angle of elevation, °

The moment arm of COM, *f* can be calculated using equation 3.34 below:

$$f = d\cos\gamma \tag{3.34}$$

where

d = length of ankle to COM, *m*

γ = angle of COM of mg, °

According to M. Dempster (1973), the center of mass (COM) of the foot is 50% of the foot length.

$$COM = 50\% \times c \tag{3.35}$$

where

c = foot length, *cm*

According to M. Dempster (1973), the segmental mass of foot can be calculated using Equation 3.36 below.

$$m = 1.45\% \times m_{body} \tag{3.36}$$

where

m = segmental mass of foot, *kg*

m_{body} = body mass, *kg*

After obtaining all the unknown variables shown in the free body diagram, ankle joint force and ankle joint moment force have been calculated as shown in Equation 3.37 to Equation 3.36 below.

$$\sum M_{ankle} = 0 \tag{3.37}$$

$$\Sigma M_c + \Sigma M_{cc} = 0$$

$$\left[(VGRF_x \times i) + \left(VGRF_y \times e\right) + \left(F_{ATy} \times e\right) + (mg \times f)\right] + [-(F_{ATx} \times i)] = 0$$

$$[(VGRF \sin\beta \times i) + (VGRF \cos\beta \times e) + (F_{AT} \sin\theta \times e) + (mg \times f)] + [-(F_{AT} \cos\theta \times i)] = 0$$

$$eF_{AT} \sin\theta - iF_{AT} \cos\theta = -[(VGRF \sin\beta \times i) + (VGRF \cos\beta \times e) + (mg \times f)]$$

$$F_{AT}(e \sin\theta - i \cos\theta) = -[(VGRF \sin\beta \times i) + (VGRF \cos\beta \times e) + (mg \times f)]$$

$$F_{AT} = \frac{-[(VGRF \sin\beta \times i) + (VGRF \cos\beta \times e) + (mg \times f)]}{(e \sin\theta - i \cos\theta)}$$

where

M_{ankle} = ankle moment, *N m*

M_{cc} = counter-clockwise moment, *N m*

M_c = clockwise moment, *N m*

$VGRF$ = vertical ground reaction force, *N*

e = length of heel tip to ankle in horizontal direction, *m*

mg = COM, *kgms*$^{-1}$

f = moment arm of COM, *m*

F_{AT} = Achilles tendon force, *N*

i = length of tip to ankle in vertical direction, *m*

Total horizontal force can be calculated using Equation 3.38 below.

$$\rightarrow + \sum F_x = 0 \tag{3.38}$$

$$F_{ATx} + A_x - VGRF_x = 0$$

$$F_{AT} \cos\theta + A_x - VGRF \sin\beta = 0$$

$$A_x = -F_{AT} \cos\theta + VGRF \sin\beta$$

where

F_{ATx} = horizontal Achilles tendon force, *N*

A_x = horizontal ankle joint force, *N*

$VGRF$ = vertical ground reaction force, *N*

Total vertical force can be calculated using Equation 3.39 below.

$$\uparrow + \sum F_y = 0 \tag{3.39}$$

$$F_{ATy} - mg + VGRF + A_y = 0$$

$$F_{AT} \sin\theta - mg + VGRF + A_y = 0$$

$$A_y = -F_{AT} \sin\theta + mg - VGRF$$

where

F_{ATy} = vertical Achilles tendon force, *N*

A_y = vertical ankle joint force, *N*

mg = COM, *kgms*$^{-1}$

$VGRF$ = vertical ground reaction force, *N*

Net ankle joint force, A can be calculated using Equation 3.40 below.

$$A = \sqrt{{A_x}^2 + {A_y}^2} \tag{3.40}$$

where
A_x = horizontal ankle joint force, N
A_y = vertical ankle joint force, N

Angle of action of ankle joint force, φ can be calculated using Equation 3.41 below.

$$\varphi = \tan^{-1}\frac{A_y}{A_x} \tag{3.41}$$

where
A_x = horizontal ankle joint force, N
A_y = vertical ankle joint force, N

3.8.4.2 Performance of Sample Calculation for Inclined High-Heeled Model

Performed sample calculation was shown below by using the sample calculation steps as shown in subsection 3.8.4.1.

Length of ankle to COM, d:

$$d = \frac{c}{2} - b$$
$$= \frac{0.23}{2} - 0.04$$
$$= 0.075\ m$$

Angle of COM of mg, γ:

$$\gamma = \sigma - \beta$$
$$= 30° - 5°$$
$$= 25°$$

Moment arm of COM, f:

$$f = d\cos\alpha$$

$$= 0.075 \cos 25°$$
$$= 0.0680\ m$$

COM:

$$COM = 50\% \times c$$
$$= 50\% \ \times 0.23$$
$$= 0.115\ m$$

Segmental mass of foot, *m*:

$$m = 1.45\% \times m_{body}$$
$$= 1.45\% \times 49.05$$
$$= 0.7112\ kg$$

Archilles tendon force, F_{AT}:

$$F_{AT} = \frac{-[(VGRF \sin\beta \times i) + (VGRF \cos\beta \times e) + (mg \times f)]}{(e \sin\theta - i \cos\theta)}$$
$$= \frac{-[(495.401 \sin 5° \times 0.13) + (495.401 \cos 5° \times 0.05) + (6.9771 \times 0.0680)]}{0.05 \sin 80° - 0.13 \cos 80°}$$
$$= -1153.6384\ N$$

Horizontal ankle joint force, A_x:

$$A_x = -F_{AT} \cos\theta + VGRF \sin\beta$$
$$= -(-1153.6384) \cos 80° + 495.401 \sin 5°$$
$$= 243.504\ \mathrm{N}$$

Vertical ankle joint force, A_y:

$$A_y = -F_{AT} \sin\theta + mg - VGRF$$
$$= -(-1153.6384)(\sin 80°) + 6.9771 - 495.401$$
$$= 647.688\ N$$

Net ankle joint force, *A*:

$$A = \sqrt{{A_x}^2 + {A_y}^2}$$
$$= \sqrt{(243.504)^2 + (647.688)^2}$$

$$= 691.950 \text{ N}$$

Angle of action of ankle joint force, φ:

$$\varphi = \tan^{-1}\frac{A_y}{A_x}$$
$$= \tan^{-1}\frac{647.688}{243.504}$$
$$= 69.40°$$

3.9 Statistical Analysis

Statistical Package for the Social Sciences (SPSS) software (IBM Corp. Released 2015 IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.) was used while performing statistical tests on collected kinetic and kinematic data. The significant level was set at .05.

3.10 Summary

Chapter 3 started off with a brief introduction in introducing the overall process that need to be follow in order to carry out this study. All and all started from planning the experiment, where the characteristics of the high-heeled shoes, weight of load, walking speed of subjects time interval of data collection and the incline slope need to be determined. Pre-testing of experiment was then carried out to assure that the flow of the whole experiment was smooth. Experiment protocol was also created to visualize the entire experiment process. Later on was the data collection, where the anthropometric measurement of subjects and the gait data need to be recorded for analysis purpose. Lastly, here comes the data processing and analysis where data extraction and normalization need to be done. The extracted data was used to do further analysis in determining the ankle joint force. The selections of parameters were supported by journals and articles that were done by previous researchers.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Statistical analysis for kinetic and kinematic parameters in different condition will be discussed in this chapter. All the data has been normalized before performing the statistical analysis to reduce the unavoidable inter-individual differences to correct the unequal anthropometric parameters of the recruited subjects.

Total of 15 healthy female subjects, age ranging from 18 to 25 years old had been recruited for this study. Overall physical characteristics of the subjects are shown in Table 4.1 below.

Table 4.1: Physical Characteristics of 15 Female Subjects.

Variables	Mean $\pm$ Standard Deviation
Age (years)	22.93 ± 0.80
Body Mass (kg)	54.04 ± 7.41
Body Height (m)	1.63 ± 0.03
Length of Leg (m)	0.94 ± 0.02

4.2 Statistical Analysis for Kinetic Parameters

Analysis of the kinetic parameters including the VGRF, ankle joint force and Achilles tendon force in different condition had been conducted. All the data had been normalized before performing the statistical analysis. Independent-means t-test was used in this statistical analysis as there are two or more experiment conditions and different participants were assigned to each condition (Field, 2009). T-value measures the size of difference relative to the variation in sample data and also a calculated difference represented in units of standard error.

4.2.1 Kinetic Statistical Analysis on Different Shoe Condition

Table 4.2 below shows the mean and standard deviation of the VGRF, ankle joint force and Achilles tendon force in different shoe condition, including barefoot and high-heels.

Table 4.2: Normalized VGRF, Ankle Joint Force and Achilles tendon Force in Different Shoe Conditions.

Parameters	Variables	Mean $\pm$ Standard Deviation	
		Barefoot	High-Heeled
VGRF	Level Unloaded	1.04 $\pm$ 0.09	1.06 $\pm$ 0.11
	Level Loaded	1.09 $\pm$ 0.11	1.10 $\pm$ 0.12
	Inclined Unloaded	1.01 $\pm$ 0.08	1.05 $\pm$ 0.13
	Inclined Loaded	1.06 $\pm$ 0.13	1.09 $\pm$ 0.10
Ankle Joint Force	Level Unloaded	0.24 $\pm$ 0.09	0.30 $\pm$ 0.05
	Level Loaded	0.32 $\pm$ 0.09	0.34 $\pm$ 0.07
	Inclined Unloaded	0.58 $\pm$ 0.25	1.04 $\pm$ 0.30
	Inclined Loaded	0.76 $\pm$ 0.30	1.96 $\pm$ 0.97
Achilles Tendon Force	Level Unloaded	-1.25 $\pm$ 0.10	-1.33 $\pm$ 0.14
	Level Loaded	-1.36 $\pm$ 0.14	-1.37 $\pm$ 0.17
	Inclined Unloaded	-1.53 $\pm$ 0.25	-2.02 $\pm$ 0.38
	Inclined Loaded	-1.74 $\pm$ 0.33	-2.98 $\pm$ 0.99

Table 4.3 below shows the statistical value of VGRF, ankle joint force and Achilles tendon force in different shoe condition, including barefoot and high heels.

Table 4.3: t-Test Result of VGRF, Ankle Joint Force and Achilles tendon Force in Different Shoe Conditions.

Parameters	Variables	Statistical Value for Barefoot vs High-Heeled			
		N	t	df	p
VGRF	Level Unloaded	15	-0.594	28	.557
	Level Loaded	15	0.259	28	.797
	Inclined Unloaded	15	-1.104	28	.279
	Inclined Loaded	15	-1.222	28	.232
Ankle Joint Force	Level Unloaded	15	-2.264	28	.031
	Level Loaded	15	-0.701	28	.489
	Inclined Unloaded	15	-4.533	28	.000*
	Inclined Loaded	15	-4.590	28	.000*

Table 4.3 (Continued)

Achilles Tendon Force	**Level Unloaded**	15	1.805	28	.082
	Level Loaded	15	-0.304	28	.763
	Inclined Unloaded	15	4.229	28	.000*
	Inclined Loaded	15	4.575	28	.000*

* = significant / p < .05.

On average, subjects experienced greater VGRF in high heels than in barefoot even though the differences were all not significant t(28) = -0.594, p >.05 for level unloaded; t(28) = -1.104, p > .05 for inclined unloaded; t(28) = 0.259, p > .05 for level loaded and t(28) = -1.222, p > .05 for inclined loaded. According to Nilsson and Thorstensson (1989), the amplitude of VGRF is approximately equal to the body weight due to the continuous contact with ground. Based on Table 4.2, the average VGRF in high heels is higher than that compared to in barefoot. This result can be supported by the study of Hyun, Kim and Ryew (2016) where VGRF showed a greater value on high heels than that of barefoot during walking due to increase of the heel height. The study of Dames and Smith (2016) also showed that walking in barefoot decreased the VGRF. According to the study of Fath, Jurek and Secoy (2016), VGRF at initial contact were significantly greater in high-heeled shoes. In barefoot static standing, the weight shifting primarily occurs through the rear foot while in high-heeled shoes are through the fore foot. The above result can be explained with an interaction of material and environmental factor, friction coefficient of floor and sensory of neuromuscular function which may cause injuries of sliding and falling etc. (Hanson, et al., 1999; Redfern and Dipasquale, 1997; Strandberg and Lanshammar, 1981; Tang and Woollacott, 1998).

On average, subjects experienced greater ankle joint force in high heels than in barefoot and the differences were not significant for level conditions, the study result obtained t(28) = -2.264, p >.05 for level unloaded; t(28) = -0.701, p >.05 for level loaded; however, the differences were significant for inclined condition, where t(28) = -4.533, p =.000 for inclined unloaded and t(28) = -4.590, p =.000 for inclined loaded. Referring to Table 4.2, the average ankle joint force in high heels is higher than that compared to in barefoot. In the study of Kalyan (2014), it shows that the ankle joint force were greater in high-heeled shoes in compared with barefoot. According to Stefanyshyn, et al. (2000), ankle joint activity showed a graded response as heel height increased. The study of Lee and Li (2014) also proved that high-heel shoes have significantly affected the ankle joint kinetic.

On the other hand, on average, subjects experienced greater Achilles tendon force in barefoot than in high heels and the differences were not significant for level conditions, the study result obtained $t(28) = 1.805$, $p > .05$ for level unloaded; $t(28) = -0.304$, $p > .05$ for level loaded; however, the differences were significant for inclined condition $t(28) = 4.229$, $p = .000$ for inclined unloaded and $t(28) = 4.575$, $p = .000$ for inclined loaded. Based on Table 4.2, the average force acted on the Achilles tendon is smaller in high-heels compared to in barefoot. Csapo, et al., (2010) stated that wearing high heels will place the calf muscle-tendon unit in a shortened position. As the muscles and tendons are highly malleable tissues, chronic use of high heels might induce structural and functional changes in the calf muscle-tendon unit. Wearing high heels thicken the Achilles tendon (Sarah, 2010) and thus the force acted on it is lower. Burnfield, et al. (2004) and Mandato and Nester (1999) concurred with the finding, stating that as the ankle joint plantar flexes, the Achilles tendon force reduces tension. The differences in ankle joint force and Achilles tendon force were significant for inclined walking for in barefoot versus in high heels. Study of Lee and Li (2014) has proven that wearing high-heels has significantly affected the ankle joint kinetic and Achilles tendon.

By comparing the result obtained, it was found that subjects experienced lower VGRF and Achilles tendon force in inclined condition compared to that of level condition. In contrast, subjects experienced greater ankle joint force in inclined condition compared to that of level condition. Lower Achilles tendon was found but as the increment of ankle joint force is much greater than that, it is said that increased in heel height may increase the risk of ankle inversion injury (Nieto and Nahigian, 1975). Moreover, it is found that the stress of the tissue may increase till a point where injury occurs if the posture acquired while wearing high-heeled shoes places demands on a joint beyond its capability (McPoil and Hunt, 1995). Therefore, it is advisable to be reducing the chances of wearing high-heeled shoes in daily life to avoid such injury to happen.

4.2.2 Kinetic Statistical Analysis on Different Load Condition

Table 4.4 below shows the mean and standard deviation of the VGRF, ankle joint force and Achilles tendon force in different load condition, including unloaded and loaded.

Table 4.4: Normalized VGRF, Ankle Joint Force and Achilles tendon Force in Different Load Conditions.

Parameters	Variables	Mean ± Standard Deviation	
		Unloaded	Loaded
VGRF	**Level Barefoot**	1.04 ± 0.09	1.09 ± 0.11
	Inclined Barefoot	1.01 ± 0.08	1.06 ± 0.13
	Level High-Heeled	1.06 ± 0.11	1.10 ± 0.12
	Inclined High-Heeled	1.05 ± 0.13	1.09 ± 0.10
Ankle Joint Force	**Level Barefoot**	0.24 ± 0.09	0.32 ± 0.09
	Inclined Barefoot	0.58 ± 0.25	0.76 ± 0.30
	Level High-Heeled	0.30 ± 0.05	0.34 ± 0.07
	Inclined High-Heeled	1.04 ± 0.30	1.96 ± 0.97
Achilles Tendon Force	**Level Barefoot**	-1.25 ± 0.10	-1.39 ± 0.14
	Inclined Barefoot	-1.53 ± 0.25	-1.74 ± 0.33
	Level High-Heeled	-1.36 ± 0.14	-1.37 ± 0.17
	Inclined High-Heeled	-2.02 ± 0.38	-2.98 ± 0.99

Table 4.5 below shows the statistical value of VGRF, ankle joint force and Achilles tendon force in different load condition, including unloaded and loaded.

Table 4.5: t-Test Result of VGRF, Ankle Joint Force and Achilles tendon Force in Different Load Conditions.

Parameters	Variables	Statistical Value for Unloaded vs Loaded			
		N	t	df	p
VGRF	**Level Barefoot**	15	-1.843	28	.076
	Inclined Barefoot	15	-1.361	28	.184
	Level High-Heeled	15	-0.818	28	.420
	Inclined High-Heeled	15	-1.423	28	.166
Ankle Joint Force	**Level Barefoot**	15	-2.478	28	.019*
	Inclined Barefoot	15	-1.743	28	.092
	Level High-Heeled	15	-1.894	28	.069
	Inclined High-Heeled	15	-3.494	28	.002*

Table 4.5 (Continued)

Achilles Tendon Force	**Level Barefoot**	15	3.103	28	.004*
	Inclined Barefoot	15	2.041	28	.051
	Level High-Heeled	15	0.779	28	.443
	Inclined High-Heeled	15	3.476	28	.002*

* = significant / $p < .05$.

On average, subjects experienced greater VGRF with loaded backpack carriage than without loaded backpack carriage even though the differences were all not significant, the result obtained $t(28) = -1.843$, $p > .05$ for level barefoot; $t(28) = -1.361$, $p > .05$ for inclined barefoot; $t(28) = -0.818$, $p > .05$ for level high-heeled and $t(28) = -1.423$, $p > .05$ for inclined high-heeled. Based on Table 4.4, the average VGRF and ankle joint force is higher with loaded carriage compared to without loaded carriage. In the study of Dames and Smith (2016), they proved that larger VGRF will be produced if the load carriage is higher. This results also supported by the study of Ang (2018), where increment of weight of load can increase the VGRF.

On average, subjects experienced greater ankle joint force with loaded backpack carriage than without loaded backpack carriage and the differences were not significant for inclined barefoot and level high-heeled, with $t(28) = -1.743$, $p > .05$ and $t(28) = -1.894$, $p > .05$ respectively; however, the differences were significant for level barefoot and inclined high-heeled, with $t(28) = -2.478$, $p = .019$ and $t(28) = -3.494$, $p = .002$ respectively. This result can be supported by the study of Chow, et al. (2005), where increased ankle joint force showed increasing demand with backpack load. In the study of Dames and Smith (2016) also showed that load carriage increases ankle joint force.

On the other hand, on average, subjects experienced greater Achilles tendon force without loaded backpack carriage than with loaded backpack carriage and the differences were not significant for inclined barefoot and level high-heeled, with $t(28) = 2.041$, $p > .05$ and $t(28) = 0.779$, $p > .05$ respectively; however, the differences were significant for level barefoot and inclined high-heeled, with $t(28) = 3.103$, $p = .004$ and $t(28) = 3.476$, $p = .002$ respectively. On the other hand, the average force acted on the Achilles tendon is smaller with loaded backpack carriage compared to without loaded backpack carriage. The obtained result is different with the outcome of the study of Willy, et al. (2019), where peak Achilles tendon had increased by 18.6% ($p < 0.001$). These discrepancies between results are probably due to different data collection and analysis method. The subjects recruited in this study are used to carrying heavy loads in daily life. When the subjects are tested in no-load condition, they are not used to the condition and tend to use more force to walk, creating more force on the Achilles tendon (Mummolo, et al., 2015).

By comparing the result obtained, it was found that subjects experienced lower VGRF and Achilles tendon force in inclined condition compared to that of level condition. In contrast, subjects experienced greater ankle joint force in inclined condition compared to that of level condition. As the increment of ankle joint force is much greater than the decrement of Achilles tendon force, the potential risk of increment in stress on bones and lead to stress fractures increases as the load increases (Jones, et al., 2000). Besides, level and uphill walking with loaded backpack carriage will lead to alterations of gait, which will increase the risk of lower extremities injuries (Lee, Yoon and Shin, 2017).

4.2.3 Kinetic Statistical Analysis on Different Slope Condition

Table 4.6 below shows the mean and standard deviation of the VGRF, ankle joint force and Achilles tendon force in different slope condition, including level and inclined.

Table 4.6: Normalized VGRF, Ankle Joint Force and Achilles tendon Force in Different Slope Conditions.

Parameters	**Variables**	**Mean ± Standard Deviation**	
		Level	**Inclined**
VGRF	**Barefoot Unloaded**	1.04 ± 0.09	1.01 ± 0.08
	Barefoot Loaded	1.09 ± 0.11	1.06 ± 0.13
	High-Heeled Unloaded	1.06 ± 0.11	1.05 ± 0.13
	High-Heeled Loaded	1.10 ± 0.12	1.09 ± 0.10
Ankle Joint Force	**Barefoot Unloaded**	0.24 ± 0.09	0.58 ± 0.25
	Barefoot Loaded	0.32 ± 0.09	0.76 ± 0.30
	High-Heeled Unloaded	0.30 ± 0.05	1.04 ± 0.30
	High-Heeled Loaded	0.34 ± 0.07	1.96 ± 0.97

Table 4.6 (Continued)

Achilles Tendon Force	**Barefoot Unloaded**	-1.25 $\pm$ 0.10	-1.53 $\pm$ 0.25
	Barefoot Loaded	-1.36 $\pm$ 0.14	-1.74 $\pm$ 0.33
	High-Heeled Unloaded	-1.33 $\pm$ 0.14	-2.02 $\pm$ 0.38
	High-Heeled Loaded	-1.37 $\pm$ 0.17	-2.98 $\pm$ 0.99

Table 4.7 below shows the statistical value of VGRF, ankle joint force and Achilles tendon force in different slope condition, including level and inclined.

Table 4.7: t-Test Result of VGRF, Ankle Joint Force and Achilles tendon Force in Different Slope Conditions.

Parameters	**Variables**	**Statistical Value for Level vs Inclined**			
		N	**t**	**df**	**p**
VGRF	**Barefoot Unloaded**	15	1.145	28	.262
	Barefoot Loaded	15	1.049	28	.303
	High-Heeled Unloaded	15	0.237	28	.815
	High-Heeled Loaded	15	-0.395	28	.696
Ankle Joint Force	**Barefoot Unloaded**	15	-4.913	28	.000*
	Barefoot Loaded	15	-5.382	28	.000*
	High-Heeled Unloaded	15	-9.367	28	.000*
	High-Heeled Loaded	15	-6.445	28	.000*
Achilles Tendon Force	**Barefoot Unloaded**	15	3.960	28	.000*
	Barefoot Loaded	15	3.872	28	.001*
	High-Heeled Unloaded	15	6.697	28	.000*
	High-Heeled Loaded	15	6.181	28	.000*

* = significant / $p < .05$.

On average, subjects experienced greater VGRF in level condition than in inclined condition even though the differences were all not significant, the study result obtained $t(28) = 1.145$, $p > .05$ for barefoot unloaded; $t(28) = 1.049$, $p > .05$ for barefoot loaded; $t(28) = 0.237$, $p > .05$ for high-heeled unloaded and $t(28) = -0.395$, $p > .05$ for high-heeled loaded. Based on Table 4.6, the average VGRF in inclined walking is lower than that compared to level walking. The result obtained can also be supported by the study of Chan, Chia and Tan

(2018), where their study showed that as incline slopes increases, VGRF decreases.

On the other hand, on average, subjects experienced greater ankle joint force in inclined condition than in level condition with the differences all significant, where t(28) = -4.913, p =.000 for barefoot unloaded; t(28) = -5.382, p =.000 for barefoot loaded; t(28) = -9.367, p =.000 for high-heeled unloaded and t(28) = -6.445, p =.000 for high-heeled loaded. Based on Table 4.6, the average ankle joint force is higher in inclined walking compared to level walking. In the study of Montgomery and Grabowski (2018), it stated that at inclined position, the ankle joint force increased at least doubled compared to in level ground position, which is correspond to the results obtained.

Besides, subjects experienced greater Achilles tendon force in level condition than in inclined condition with the differences all significant, where t(28) = 3.960, p =.000 for barefoot unloaded; t(28) = 3.872, p =.001 for barefoot loaded; t(28) = 6.697, p =.000 for high-heeled unloaded and t(28) = 6.181, p =.000 for high-heeled loaded. Based on Table 4.6, the average force acted on the Achilles tendon is smaller in inclined walking compared to level walking. Greater Achilles tendon force while inclined walking is similar with previously published data (Neves, 2014), where the Achilles tendon is affected while moving the leg.

On average, effect of slope condition on ankle joint force and Achilles tendon force is found ($p < .05$), but there was no effect of slope condition on VGRF ($p > .05$). Greater ankle joint force while inclined walking is in line with previously published data (Alexander, et al., 2017; Farris and Sawicki, 2012).

4.3 Statistical Analysis for Kinematic Parameters

Analysis of the kinematic parameters including the cadence, stride length and step length in different condition had been conducted. All the data had been normalized before performing the statistical analysis. Independent-means t-test was used in this statistical analysis as there are two or more experiment conditions and different participants were assigned to each condition (Field, 2009). T-value measures the size of difference relative to the variation in sample data and also a calculated difference represented in units of standard error.

4.3.1 Kinematic Statistical Analysis on Different Shoe Condition

Table 4.8 below shows the mean and standard deviation of the cadence, stride length and step length in different shoe condition, including barefoot and high-heels.

Table 4.8: Normalized Cadence, Stride Length and Step Length in Different Shoe Conditions.

Parameters	Variables	Mean ± Standard Deviation	
		Barefoot	High-Heeled
Cadence	**Level Unloaded**	0.448 ± 0.031	0.445 ± 0.045
	Level Loaded	0.445 ± 0.035	0.440 ± 0.036
	Inclined Unloaded	0.447 ± 0.024	0.443 ± 0.024
	Inclined Loaded	0.443 ± 0.035	0.439 ± 0.029
Stride Length	**Level Unloaded**	1.147 ± 0.054	1.130 ± 0.080
	Level Loaded	1.143 ± 0.244	1.090 ± 0.246
	Inclined Unloaded	1.140 ± 0.196	1.111 ± 0.322
	Inclined Loaded	1.130 ± 0.237	1.080 ± 0.510
Step Length	**Level Unloaded**	0.574 ± 0.027	0.565 ± 0.040
	Level Loaded	0.572 ± 0.122	0.545 ± 0.123
	Inclined Unloaded	0.570 ± 0.098	0.556 ± 0.161
	Inclined Loaded	0.565 ± 0.119	0.540 ± 0.255

Table 4.9 below shows the statistical value of cadence, stride length and step length in different shoe condition, including barefoot and high heels.

Table 4.9: t-Test Result of Cadence, Stride Length and Step Length in Different Shoe Conditions.

Parameters	Variables	Statistical Value for Barefoot vs High-Heeled			
		N	t	df	p
Cadence	**Level Unloaded**	15	2.348	28	.056
	Level Loaded	15	2.489	28	.069
	Inclined Unloaded	15	-1.743	28	.092
	Inclined Loaded	15	-1.298	28	.205

Table 4.9 (Continued)

Stride Length	**Level Unloaded**	15	0.714	28	.481
	Level Loaded	15	0.593	28	.558
	Inclined Unloaded	15	0.290	28	.774
	Inclined Loaded	15	-0.232	28	.818
Step Length	**Level Unloaded**	15	0.714	28	.481
	Level Loaded	15	0.593	28	.558
	Inclined Unloaded	15	0.290	28	.774
	Inclined Loaded	15	-0.232	28	.818

* = significant / $p < .05$.

On average, greater cadence is found in subjects in barefoot than in high heels even though the differences were all not significant, where $t(28) = 2.348$, $p > .05$ for level unloaded; $t(28) = 2.489$, $p > .05$ for level loaded; $t(28) = -1.743$, $p > .05$ for inclined unloaded and $t(28) = -1.298$, $p > .05$ for inclined loaded. Based on Table 4.8, the average cadence in high heels is lower than that compared to in barefoot. In the study of Fath, Jurek and Secoy (2016), they illustrated that cadence decreased in high-heeled shoes, regardless of the plane of walking, either level or uphill. According to Ang (2018), the results of his study revealed that as heel height increases, the cadence for walking in barefoot is higher than walking in high-heeled shoes.

On the other hand, on average, greater stride length is found in subjects in barefoot than in high heels even though the differences were all not significant, where $t(28) = 0.714$, $p > .05$ for level unloaded; $t(28) = 0.593$, $p > .05$ for level loaded; $t(28) = 0.290$, $p > .05$ for inclined unloaded and $t(28) = -0.232$, $p > .05$ for inclined loaded. Based on Table 4.8, the average strides length and step length in high heels is lower than that compared to in barefoot. However, in the study of Dames and Smith (2016) shows that barefoot walking elicited shorter stride length, which does not match the results obtained. The differences in results are probably due to different data collection and analysis method. On the other hand, the results obtained is similar with the outcome of the study of Ang (2018), where both of the study used the similar data collection and analysis method, and his results stated that as heel height increased, both stride length and step length were decreased.

4.3.2 Kinematic Statistical Analysis on Different Load Condition

Table 4.10 below shows the mean and standard deviation of the cadence, stride length and step length in different load condition, including unloaded and loaded.

Table 4.10: Normalized Cadence, Stride Length and Step Length in Different Load Conditions.

Parameters	Variables	Mean ± Standard Deviation	
		Unloaded	Loaded
Cadence	Level Barefoot	0.448 ± 0.031	0.445 ± 0.035
	Inclined Barefoot	0.447 ± 0.024	0.443 ± 0.035
	Level High-Heeled	0.445 ± 0.045	0.440 ± 0.036
	Inclined High-Heeled	0.443 ± 0.024	0.439 ± 0.029
Stride Length	Level Barefoot	1.147 ± 0.054	1.143 ± 0.244
	Inclined Barefoot	1.140 ± 0.196	1.130 ± 0.237
	Level High-Heeled	1.130 ± 0.080	1.090 ± 0.246
	Inclined High-Heeled	1.111 ± 0.322	1.080 ± 0.510
Step Length	Level Barefoot	0.574 ± 0.027	0.572 ± 0.122
	Inclined Barefoot	0.570 ± 0.098	0.565 ± 0.119
	Level High-Heeled	0.565 ± 0.040	0.545 ± 0.123
	Inclined High-Heeled	0.556 ± 0.161	0.540 ± 0.255

Table 4.11 below shows the statistical value of cadence, stride length and step length in different load condition, including unloaded and loaded.

Table 4.11: t-Test Result of Cadence, Stride Length and Step Length in Different Load Conditions.

Parameters	Variables	Statistical Value for Unloaded vs Loaded			
		N	t	df	p
Cadence	Level Barefoot	15	-0.323	28	.749
	Inclined Barefoot	15	-0.571	28	.573
	Level High-Heeled	15	-0.331	28	.743
	Inclined High-Heeled	15	-0.644	28	.525

Table 4.11 (Continued)

Stride Length	**Level Barefoot**	15	-1.488	28	.148
	Inclined Barefoot	15	0.115	28	.909
	Level High-Heeled	15	-0.912	28	.370
	Inclined High-Heeled	15	-0.339	28	.737
Step Length	**Level Barefoot**	15	-1.488	28	.148
	Inclined Barefoot	15	0.115	28	.909
	Level High-Heeled	15	-0.912	28	.370
	Inclined High-Heeled	15	-0.339	28	.737

* = significant / p < .05.

In the study of Dames and Smith (2016), it showed that load carriage will increase the stance, regardless of the footwear chosen. The study of Thakurta, et al. (2016) also claimed that the walking patterns in female were affected by the increased load. On average, greater cadence is found in subjects without loaded backpack carriage than with loaded backpack carriage even though the differences were all not significant, where $t(28) = -0.323$, $p > .05$ for level barefoot; $t(28) = -0.571$, $p > .05$ for inclined barefoot; $t(28) = -0.331$, $p > .05$ for level high-heeled and $t(28) = -0.644$, $p > .05$ for inclined high-heeled. Based on Table 4.10, the average cadence with loaded backpack carriage is lower than that compared to without loaded backpack carriage. In the study of Chow, et al. (2005), it said that with increasing of backpack load, the walking speed and cadence were decreased.

On the other hand, on average, greater stride length is found in subjects without loaded backpack carriage than with loaded backpack carriage even though the differences were all not significant, where $t(28) = -1.488$, $p > .05$ for level barefoot; $t(28) = 0.115$, $p > .05$ for inclined barefoot; $t(28) = -0.912$, $p > .05$ for level high-heeled and $t(28) = -0.339$, $p > .05$ for inclined high-heeled. Based on Table 4.10, the average strides length and step length with loaded backpack carriage is lower than that compared to without loaded backpack carriage. This result can be supported by the study of Thakurta, et al. (2016), where they proved that stride length were reduced while the stride rate and double-support time were risen with the increased load. Thus, stride length and step length tend to be decreased as the load increased.

4.3.3 Kinematic Statistical Analysis on Different Slope Condition

Table 4.12 below shows the mean and standard deviation of the cadence, stride length and step length in different slope condition, including level and inclined.

Table 4.12: Normalized Cadence, Stride Length and Step Length in Different Slope Conditions.

Parameters	**Variables**	**Mean ± Standard Deviation**	
		Level	**Inclined**
Cadence	**Barefoot Unloaded**	0.448 ± 0.031	0.447 ± 0.024
	Barefoot Loaded	0.445 ± 0.035	0.443 ± 0.035
	High-Heeled Unloaded	0.445 ± 0.045	0.443 ± 0.024
	High-Heeled Loaded	0.440 ± 0.036	0.439 ± 0.029
Stride Length	**Barefoot Unloaded**	1.147 ± 0.054	1.140 ± 0.196
	Barefoot Loaded	1.143 ± 0.244	1.130 ± 0.237
	High-Heeled Unloaded	1.130 ± 0.080	1.111 ± 0.322
	High-Heeled Loaded	1.090 ± 0.246	1.080 ± 0.510
Step Length	**Barefoot Unloaded**	0.574 ± 0.027	0.570 ± 0.098
	Barefoot Loaded	0.572 ± 0.122	0.565 ± 0.119
	High-Heeled Unloaded	0.565 ± 0.040	0.556 ± 0.161
	High-Heeled Loaded	0.545 ± 0.123	0.540 ± 0.255

Table 4.13 below shows the statistical value of cadence, stride length and step length in different slope condition, including level and inclined.

Table 4.13: t-Test Result of Cadence, Stride Length and Step Length in Different Slope Conditions.

Parameters	Variables	Statistical Value for Level vs Inclined			
		N	t	df	p
Cadence	**Barefoot Unloaded**	15	1.450	28	.158
	Barefoot Loaded	15	0.969	28	.341
	High-Heeled Unloaded	15	-2.562	28	.056
	High-Heeled Loaded	15	-2.956	28	.056
Stride Length	**Barefoot Unloaded**	15	-1.756	28	.090
	Barefoot Loaded	15	0.150	28	.882
	High-Heeled Unloaded	15	-0.955	28	.348
	High-Heeled Loaded	15	-0.504	28	.618
Step Length	**Barefoot Unloaded**	15	-1.756	28	.090
	Barefoot Loaded	15	0.150	28	.882
	High-Heeled Unloaded	15	-0.955	28	.348
	High-Heeled Loaded	15	-0.504	28	.618

* = significant / $p < .05$.

On average, greater cadence is found in subjects in level walking than in inclined walking even though the differences were all not significant, where $t(28) = 1.450$, $p > .05$ for barefoot unloaded; $t(28) = 0.969$, $p > .05$ for barefoot loaded; $t(28) = -2.562$, $p > .05$ for high-heeled loaded and $t(28) = -2.956$, $p > .05$ for high-heeled loaded. Based on Table 4.12, cadence was found to be decreasing with the increasing of inclined slope. These findings has been supported by other studies (Gottschall and Kram, 2005; Padulo, et al., 2013). As stated in the study of Swanson and Caldwell (2000), increasing of incline slopes would resulting in the increment of metabolic variables, such as heart rate, metabolic cost and oxygen consumption blood lactate. The increment in metabolic variables will also increase the cadence (Padulo, et al., 2013).

On the other hand, on average, greater stride length is found in subjects in level walking then in inclined walking even though the differences were all not significant, where t(28) = -1.756, p >.05 for barefoot unloaded; t(28) = 0.150, p >.05 for barefoot loaded; t(28) = -0.966, p >.05 for high-heeled loaded and t(28) = -0.504, p >.05 for high-heeled loaded. Franz, Lyddon and Kram (2012) stated that a stride changes when walking on level and uphill ground. Based on Table 4.12, it was found that inclined walking had a smaller stride length and step length compared to level walking. The result obtained can be supported by the study of Chan, Chia and Tan (2018), where their study results showed that stride length and step length decreases with the increasing of slope.

4.4 Summary

This chapter discussed about the results obtained, as well as the statistical analysis, and effects of different shoe, load and slope condition acted onto the ankle joint. Kinetic and kinematic analyses were discussed.

In this study, it was found that as heel height increased, Achilles tendon force significantly decreased and ankle joint force significantly increased. As the increase ratio of the ankle joint force is much greater than the decrease ratio of the Achilles tendon force, there will be risk of ankle inversion injury (Nieto and Nahigian, 1975). Various studies reported that when the foot is positioned in a high-heeled shoe, several changes can be observed (Burnfield, et al., 2004; Ebbeling, Hamill and Crussemeyer, 1994; Mandato and Nester, 1999; Ricci and Karpovich, 1964; Schwartz and Heath, 1959). As an example, the ankle joint axis moves in anterior position and the line of gravity moves in posterior position towards the ankle joint (Burnfield, et al., 2004; Mandato and Nester, 1999). The foot becomes shorter as the arch rose (Schwartz and Heath, 1959). Ebbeling, Hamill and Crussemeyer (1994) investigated that the biomechanics of the lower limb as a function of heel height. They found that as heel height increases, there is a graded increase found in the maximum rear foot eversion angle until the highest heel condition. In high-heeled shoes, the ankle joint has a greater freedom of frontal plane motion and therefore it is mechanically unstable which will cause injury to the gait movement of women (Cowley, Chevalier and Chockalingam, 2009). Studies by Ebbeling, Hamill and Crussemeyer

(1994) proposed that energy consumed in high-heeled gait is higher than that of low-heeled gait which will lead to fatigue, where reflex, voluntary response rates and strength will be reduced. As discussed in previous sections, increasing in heel height will reduce the stability of subject. In the study of Lord and MBBS (1996), they demonstrated that postural stability of subject while wearing high-heeled shoes can be improved by increasing the base area of the heel tip.

Lee, Yoon and Shin (2017) investigated that alterations of gait due to load carriage may increase the risk of lower extremity injuries. Joint force of the lower extremities and VGRF increased as the weight of load increases (Pigrrynowsi, Norman and Winter, 1981). Generally, increase in weight of load carriage will lead to potential risk for musculoskeletal injury of the lower limbs (Vacheron, et al., 1999; Harman, et al., 2000). In addition, suggestion has been provided that additional of backpack load will increase the stress on bones of human and will eventually lead to stress fracture to the subject (Jones, et al., 2000). In this study, it was found that Achilles tendon force significantly decreased and ankle joint force significantly increased. As the ratio of the ankle joint force increment is more than the ratio of the Achilles tendon force decrement, there will be a high potential risk of increment in stress on bones and lead to stress fractures on the subject (Jones, et al., 2000).

Previous study proposed that 80% of the overall mechanical leg work required in level walking depends on the muscles surrounding ankle joint and it differs in magnitude while walking uphill (Winter, 1983). It was found that the force acting onto the ankle joint generated greater during uphill walking compared to that of level walking (Lay, et al., 2007). Montgomery and Grabowski (2018) found that the ankle joint force increased with uphill slopes and walking up a steeper slope requires more joint force. It is suggested to decrease the number of uphill walking in order to reduce comorbidities such as low back pain that incurred in person with impaired or no ankle function (Ehde, et al., 2001; Emphraim, et al., 2005; Grabowski and D’Andrea, 2013). On average, the effect of slope condition on ankle joint force and Achilles tendon force is found, where it significantly affects the results. As the increase ratio of the ankle joint force is much greater than the decrease ratio of the Achilles tendon force, the potential of injury made to the subject increased.

In short, as heel height, weight of load and level of slope increases, ankle joint force significantly increased and Achilles tendon force significantly decreased; while cadence, stride length and step length were reduced. Increase in ankle joint force will cause fellow women to suffer from detrimental effects. Studies of Dames and Smith (2016) showed that increment of ankle joint force will lead to imbalance posture and gait movement of women. Despite the height of the heel, wearing high-heeled shoes will give rise to the alterations in balancing. Besides, additional of backpack load carriage will also increase the risk of musculoskeletal injury while uphill walking might cause lower back pain. Therefore, it is advisable that women should decrease the number of wearing high-heeled shoes while carrying backpack load and walking uphill in their daily life.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In a nutshell, the biomechanics effects on ankle joint by varying the weight of load carriage, the heel height of the high-heeled shoes and the level of slope while walking had been investigated. Mathematical model in determining ankle joint force by using inverse dynamic approach had also been developed. This study also resulted that walking with backpack load carriage, high-heeled shoes and inclined slope will alter the kinetics of lower extremities. Ankle joint force significantly increased and Achilles tendon force significantly decreased as heel height, weight of load and level of slope increased. As for kinematic parameters, as the heel height, weight of load and level of slope increases, the cadence, stride length and step length were reduced.

5.2 Recommendations for future work

First and foremost, in this study, the angles used in the free body diagrams for calculating purposes were determined using “Kinovea” software, which is a video-based recording system. Yet, the recorded video might not be exactly from the same plane and it might indirectly affect the accuracy of the result. Thus, more flexible, wearable and less restraints sensors can be introduced as a replacement for the video-based recording system. This method is also able to create real-time angles that are suitable for long term monitoring with simple reconstruction algorithm with small output volume from the sensors.

Besides, the motion of subjects walking is in 3-dimensional motion. Therefore, 3-dimentional motion capture system can be introduced. Unknown angles can be easily obtained by using the 3-dimentional motion capture system, which can improve the accuracy of the results obtained. The results obtained then can be applied in the mathematical model in determining the forces.

On the other hand, the force plate used in the study was the piezoelectric sensor platform which was unable to measure the pressure of the subjects (Chan, Chia and Tan, 2018). Thus, pressure insoles can be introduced in determining the pressure distribution of foot during level and uphill walking.

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APPENDICES

Table A: Anthropometric Measurements of Subjects

Parameters	Data
Name	
Age	
Body Height (cm)	
Body Mass (kg)	
Heel Height, *a* (cm)	
Length of Heel to Ankle, *b* (cm)	
Foot Length, *c* (cm)	
Length of Heel Tip to Ankle in horizontal direction, *e* (cm)	
Length of Heel Tip to Ankle in vertical direction, *i* (cm)	
Leg Length, l_o (cm)	
Angle between High-Heeled Shoes and Inclined Plane, σ (°)	