# BIOMECHANICAL INVESTIGATION OF INDIVIDUAL WITH OVER-PRONATION AND OVER-SUPINATION FOOT DURING WALKING

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FACULTY OF ENGINEERING
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**DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE**

**FACULTY OF ENGINEERING**
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**ORIGINAL LITERARY WORK DECLARATION**

Name of Candidate: Nur Saibah binti Ghani

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Name of Degree: Master of Engineering Science

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Biomechanical Investigation of Individual with Over-Pronation and Over-Supination Foot during Walking

Field of Study: Biomedical Engineering

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## ABSTRACT

Over-pronation and over-supination foot conditions are foot deformity that can lead to unstable ankle and subtalar joint during walking. They are define as condition where the foot roll in and out excessively from its neutral line and can lead to misalignment of the foot and leg in human in which can create abnormal gait cycle. Therefore, the purposes of this study are to analyze the foot-ankle joint biomechanical behavior including the range of motion, joint moment, joint power and GRF in a complete gait cycle for all subjects in this study and to compare the foot-ankle biomechanical behavior between normal foot with over-pronation and over-supination foot condition during walking. 20 subjects were volunteer but only 16 passed the selection test and divided into three groups; normal subjects (n=2), over-pronation (n=7) and over-supination (n=7). Motion analysis system was used to observe and analyze the gait cycle in individual with over-pronation and over-supination conditions. The raw data that we got from motion analysis will be statistically analyzed using the Vicon™ Nexus 1.3 and MATLAB_R2019a software. The result observed were kinematics and kinetic parameter of foot during walking. The statistical analysis done to compare normal foot with OP foot condition shows that the ankle joint during the initial contact was below 5° for all subjects. Subject 2 shows the lowest ankle angle during initial contact while for mid stance phase, subject 3 shows the highest ankle angle which was 24.15° on left foot and 28.30° on right foot. From the ANOVA test, the p-value for ankle joint angle was less than 0.05, which indicates that there was significant difference between all the subjects. For joint moment and power the p-values found was less than 0.05 which indicates there was significance differences between over-pronation compare to normal foot condition. While for subjects with over-supination condition, they tends to be in plantar flexion condition during heel strike phase rather than in neutral position because the high arch put the foot in plantar flexion position such as subject 1(-0.69), subject 3 (-

0.33°), subject 5 (-0.38°) and subject 7 (-4.55°). While the normal subject starts this phase at neutral position (0°) and a little dorsiflexion (2.97°). The statistical analysis for kinetic and kinematic data when comparing over-supination foot condition with normal foot condition shows that the p-values were more than 0.05 that indicates there were no significant differences between these two conditions. Therefore, this research concluded that the analyzed done on kinetic and kinematic data to demonstrate that the ankle joint angle, moment, power and GRF does in fact influence by the condition of the foot and can cause deformities if no proper treatment was done.

*Keywords: Over-pronation, Over-supination, Kinematic, Kinematic, Gait Cycle*

# ABSTRAK

Lebihan pergerakan didalam keadaan pronate dan supinate adalah salah satu masalah kaki yang boleh menyebabkan sendi kaki yang tidak stabil. Hal ini berlaku kerana buku lali mungkin berada dalam keadaan ke dalam atau luar yang berlebihan daripada normal dan boleh menyebabkan kaki tidak berada di posisi yang normal. Oleh itu, kajian ini bertujuan untuk mengkaji perkara yang berkaitan dengan biomekanikal kaki dan buku lali termasuk julat pergerakan sendi, momen kaki, kuasa sendi dan daya yang berlaku ke atas sendi dan membandingkan di antara keadaan kaki yang normal dan kaki yang mempunyai lebihan pronate dan supinate semasa berjalan. Kajian ini juga akan menyediakan data yang akan membantu membetulkan masalah ini. 20 subjek dengan sukarela ingin menyertai penyelidikan ini, tetapi hanya 16 subjek yang terpilih selepas ujian pemilihan dijalankan. Meraka kemudian dibahagikan kepada 3 kumpulan iaitu kumpulan biasa (n=2), lebihan pronate (n=7) dan lebihan supinate (n=7). Analisa pergerakan digunakan untuk memerhati dan menganalisis pergerakan ketika berjalan dan sudut buku lali bagi individu yang mempunyai masalah yang disebabkan lebihan pergerakan daripada keadaan supinate dan pronate. Keputusan yang diperolehi melalui analisa pergerakan akan dianalisa secara statistik menggunakan sistem $Vicon^{TM}$ *Nexus 1.3* dan *MATLAB_R2019a*. Keputusan yang diperhatikan adalah parameter kinematik kaki dan buku lali iaitu sudut dan kuasa. Hasil kajian menunjukan suduk buku lali semasa tumit menyentuh permukaan adalah dibawah 5° kecuali individu yang ke 2. Semasa tapak kaki berada dalam keadaan mendatar, individu ke 2 turut menunjukan sudut buku lali yang rendah berbanding individu normal. Melalui kajian statistic ANOVA, nilai p untuk sudut buku lali adalah kurang daripada 0.05, ini menunjukan terdapat berbezaan yang nyata antara subjek yang menjalankan kajian. Di samping itu, parameter lain menunjukan nilai p kurang daripada 0.05 dan membuktikan bahawa terdapat perbezaan diantara keadaan kaki yang normal dan keadaan terlebih pronate. Manakala, untuk subjek dengan keadaan terlebih supinate, mereka cenderung untuk berada dalam keadaan kaki kebawah semasa fasa tumit mencecah ke tanah disebabkan oleh keadaan kaki yang terlebih supinate. Subjek 1 (-0.69°), subjek 3 (-0.33°), subjek 5 (-0.38°) dan subjek 7 (-4.55°) manakala untuk subjek normal (0°) dan (2.97°). Analisis statistic menunjukan nilai p lebih daripada 0.05 bagi semua parameter yang telah dikaji. Oleh yang demikian, melalui kajian ini, jelas menunjukan bahawa semua parameter kinematic dan kinetic adalah bergantung dengan keadaan kaki seseorang dan sekiranya tiada rawatan yang sempurna ia akan menyebabkan kecacatan di masa depan.

*Kata kunci: Lebihan pronate, lebihan supinate, Kinematik, Kinetik, Kitaran berjalan*

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| | | |
|---|---|---|
| ADLs | : | Activity of daily living |
| CoP | : | Center of Pressure |
| GRF | : | Ground Reaction Force |
| ICF | : | International Classification of Functioning Disabilities and Health |
| WHO | : | World Health Organization |
| FPI | : | Foot Posture Index |
| CPO | : | Certified Prosthetist and Orthotist |
| ISPO | : | International Society of Prosthetics and Orthotics |

# LIST OF APPENDICES

# CHAPTER 1: INTRODUCTION

This chapter provide overview regarding the literature review of biomechanical investigation of individual with over-pronation and over-supination foot during walking that become motivation for this study. This chapter also includes the objectives of this study, scope of work and thesis organization.

## 1.1 Overview

Foot is function to provide a foundation support of the upright body and help the body to propel forward during locomotion. Foot deformity and pain had gradually increase and become one of the major disabilities to the Malaysia community as reported in the National Health Morbidity Survey ((IPH)) that disability in walking was 11.3% of overall population in Malaysia (Malaysia, 2015). In this study, the focus was on individual with over-pronation and over-supination foot during walking. These two conditions can be consider as foot deformities that can happen to people in which can lead to unstable ankle and subtalar joint in future if they go without treatment.

These problems happen due to excessive inversion or eversion that can lead to misalignment of the foot during standing and moving (Hintermann & Nigg, 1998). These deformity will cause looseness and/or giving away of the joint and they usually associated with ankle instability. Supported by the researchers study that concluded that rotational angle of plantar flexion and dorsiflexion affects the rotation ranges of supination and pronation (Xiao, Zhang, Zhao, & Wang, 2017). Another study by Krähenbühl et al.,2017 suggest that subtalar joint instability may occur when there was a malfunction of the interosseous talocalcaneal ligament in combination with failure of the anterior ligament that leads to an abnormal function of the anterolateral rotation of talus during gait (Krähenbühl, Horn-Lang, Hintermann, & Knupp, 2017). Other factor that can be associated with the stability of subtalar joint is the calcaneofibular ligament (Ringleb, Dhakal, Anderson, Bawab, & Paranjape, 2011).

Supination and pronation movement are also known as side to side movement of the foot-ankle that mainly control by subtalar joint. (Krähenbühl et al., 2017). These two movements are importance as movement aids in walking or running especially on uneven surfaces. But in dealing with activity of daily living (ADLs), some people tend to be in over-pronation (ankle over outward) and over-supination (ankle over inward) during walking or running. These can lead to foot-ankle joint instability which can cause abnormality of foot arch, misalignment of the foot and gait deviation. Kakihana et al., 2005 stated that subjects with laterally shifted center of pressure (CoP) when walking due to unstable lateral ankle will produce a large ground reaction force (GRF) under the lateral aspect of the foot (Kakihana et al., 2005). Furthermore, the stability of the foot will be impaired and can lead to patellofemoral pain or foot pain when excessive compensatory pronation of subtalar joint occurs during weight-bearing activity (Shih, Wen, & Chen, 2011).

Biomechanical evidence supports that altered lower limb alignment can lead to extremes changes of the foot posture and function (Riskowski et al., 2013). Over-pronation and over-supination can lead to future injury and chronic function instability of the foot such as ankle and subtalar joint instability if no proper treatment is carried out. Besides that, Mitchell et al.,2005 believes that the unstable subtalar joint will have slower reaction time to induce ankle sprain mechanism compared to a stable joint (Mitchell, Dyson, Hale, & Abraham, 2008). Biomechanical abnormalities in gait can cause inversion sprain which is importance in gait and sport (Willems, Witvrouw, Delbaere, De Cock, & De Clercq, 2005).

The current treatment and orthotic intervention for this deformity had yet to find it maximum solution as most of the study only correct the position of the foot without accommodate the joint and realign the entire alignment of the leg by considering the ankle delimitation. By right, there should be guidance or at least the delimitation of ankle movement so that the physiotherapies, and sport trainer know where to put the boundaries in explaining the ankle delimitation to the subject. The joint instability may as well lead to the relationship between the human weight anthropometry, which may lead to calculate the human body mass that contribute to the ankle movements. Those who are currently with the disability may use an orthotic insole, but again, how this insole should be design by the prosthetist/orthotist in providing the best insole that required considering the ankle delimitation. Furthermore, the product in the market for people with over-pronation and over-supination foot was less cosmetic and bulky for the subject.

Therefore, the main objectives of this study were to analyze the foot-ankle joint biomechanical behavior including the range of motion, joint moment, joint power and GRF in a complete gait cycle for all subjects in this study and to compare the foot-ankle biomechanical behavior between normal foot with over-pronation and over-supination foot condition during walking in order to provide data to correct the deformity.

## 1.2 Problem statement and Aim

Foot deformity and pain had gradually increase and become one of the major disabilities to the Malaysia community as reported in the National Health Morbidity Survey ((IPH)) that disability in walking was 11.3% of overall Malaysia population. The actual statistic on the foot deformity and pain could be much higher than that of been reported because people tend to ignore the foot pain or take it as a normal aging disease. In fact, the ignorance of the community in foot deformity and pain slowly affected their activity level and productivity, which directly cause a drop in the quality of life.

Foot orthotic or insole seems to be the most preferable non-invasive treatment to foot deformity and pain, as most of the cases are related to foot-ankle misalignment, including the foot-ankle joint instability. Foot orthotic is a device where its function to realign the foot, accommodate the foot, and prevent further deformity. Foot-ankle misalignment could be due to congenital or developmental, in the sense that someone might born with the foot disorder but there is also possibility that someone overuse their foot-ankle till it gets deformed. In the cases of, joint instability the causes can be due to the congenital or due to the trauma or injury. Subtalar instability is a condition that is characterized by the looseness and/or giving away of the joint and it is usually associated with ankle instability. The loosening of the joint is caused by the injury of the ligament of the subtalar joint and sometimes due to the previous ankle injury that goes without treatment.

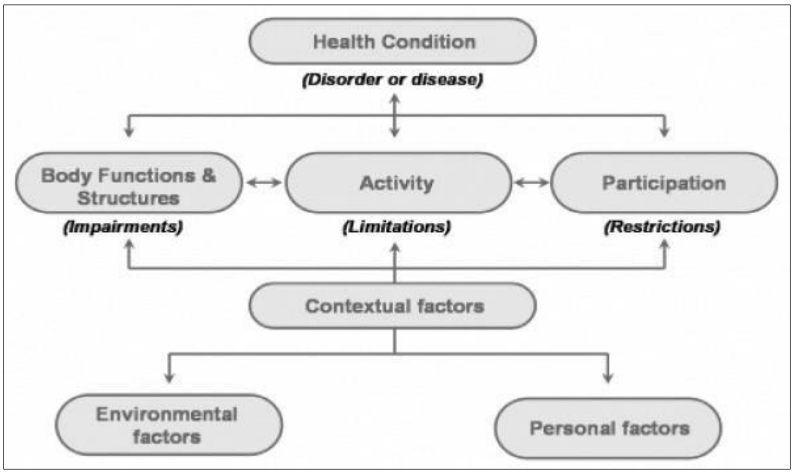


Figure 1.1: International Classification of Functioning, Disabilities and Health by World Health Organization (WHO) (Nixon, Hanass-Hancock, Whiteside, & Barnett, 2011)

According to ICF that established by WHO, health conditions could be determined by several attributes. Foot-ankle misalignment which is due to over-pronation and over-supination foot condition can cause the impairment of the body structure, which will lead to body functions impairment eventually if it is not treated. These foot condition can lead to subtalar and ankle instability. Where they can cause pain and limits the activity of the pain bearer in terms of walking and also can restrict their participation within the community. Therefore, over-pronation and over-supination foot are definitely foot disorder according to the explanation using the ICF (Figure 1.1).

Thus, the aim of this study is to know whether the biomechanical evaluation throughout individual with over-pronation and over-supination foot during walking can help to prevent these deformities and help people to do sport or exercise.

## 1.3 Objectives of Thesis

This research and study are intended to:

1. To analyze the foot-ankle joint biomechanical behavior including the range of motion, joint moment, joint power and GRF in a complete gait cycle for all subjects in this study
2. To compare the foot-ankle biomechanical behavior between normal foot with over-pronation and over-supination foot during walking and provide data to assist future development of therapeutic devices.

## 1.4 Scope of work

This study will investigate the biomechanical of individual with over-pronation and over-supination foot during walking using the motion analysis laboratory. The result that obtained in this study will be compare with the normal individual and the difference will be evaluated. From the results obtained, proper guideline will be provided to help in future treatment in recovery process.

## 1.5 Thesis Organization

Five chapters in this thesis will cover the introduction, literature review, methodology, results and discussion and lastly the conclusion part.

Chapter one basically was cover the main idea about this study and they will be general outline regarding this study which briefly introduction about the literature review for biomechanical investigation of individual with over-pronation and over-supination foot during walking that give motivation to do this study. The highlight for this chapter were justification regarding the problem statement, objectives, scope of the work and thesis organization.

Next was chapter two in which will cover about the literature review and related study with this topic. This includes the review on the anatomy and biomechanical of foot-ankle joint, over-pronation and over-supination. Literature review also done about the diagnosis and treatment regarding this problem.

Chapter three was the explanation about the method used to do this study in which includes the subject selection, ethical approval, experimental procedure and data analysis. This chapter will give detail on how suitable subjects were selected for this study and also explanation about the complete experimental procedure of this study.

Chapter four was focus on the results and discussion obtained from this study. The results about the biomechanical investigation of individual with over-pronation and over-supination foot during walking were illustrated using suitable tables and figures.

Chapter five was the conclusion about the finding of the study either the objective was achieved or not. This chapter also covers about limitation of this study and future improvement plan that can be done.

## 1.6 Flowchart of Study

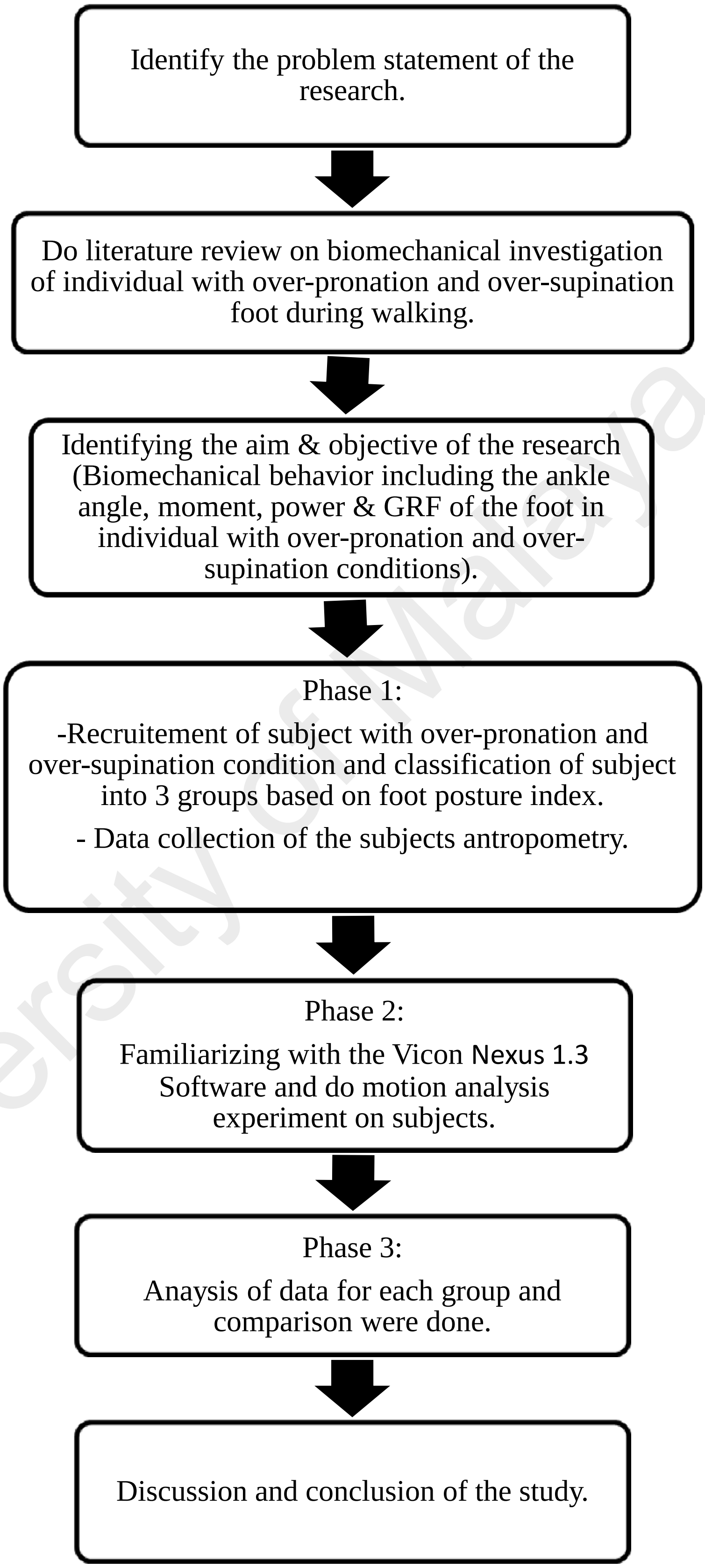


Figure 1.2: The flowchart of the study

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

This chapter will provide information regarding the biomechanical investigation of individual with over-pronation and over-supination foot during walking to help in generate proper protocol for methodology part. For this chapter, there will be seven sub-topics regarding this study that will be used as the references and motivation to show the importance of biomechanical analysis of the foot and proper treatment that can be used to treat the subject.

## 2.2 Anatomy and biomechanics of foot-ankle joint

Foot is an importance structure in human body that provides a foundation support for the upright body in order to help in locomotion. Foot are consists of 26 bones and 33 joints in which 20 of them are actively articulated and lots of muscles, nerves, ligaments of differences types that help to adapt during uneven terrain and absorb shock (Hall, 1999). There are 6 importance movement of the foot as in Figure 2.1. The movement can be observed according to the body plane, as in sagittal plane there are dorsiflexion and plantar flexion movement, for the frontal plane there are inversion and eversion movement. While for the transverse plane are adduction and abduction of the foot (Chan & Rudins, 1994). All these movements are associated with the musculoskeletal system that generated forces to produces the movement and propel the body forward. Thus, it is importance to know about the anatomy of the foot in order to understand the biomechanical of the foot.

During movement, the shape of the foot is changing in order to absorb the force that acting on the body and allow the movement to happen. For example, the foot will react starting from heel and moving forward along the sole to the force that happen on the body during movement such as ground reaction force (GRF) that counter the gravity force and also the internal force that being produce by the muscle.

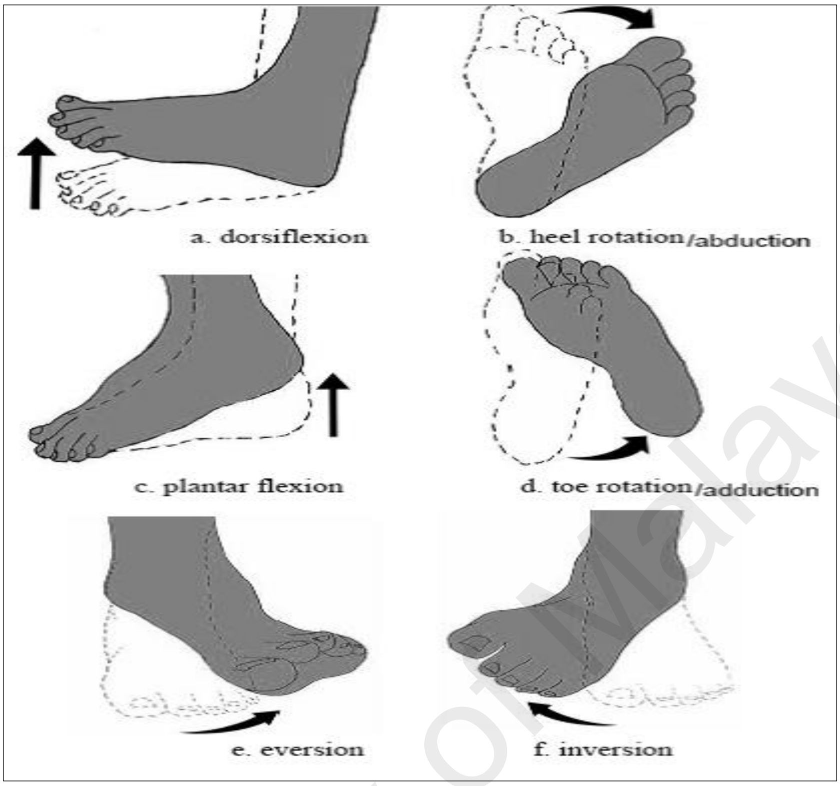


Figure 2.1: The movement of the foot. Retrieved from: (Gunawardena & Hirakawa, 2015)

### 2.2.1 Bone of foot

The bones in the foot and anatomically the bones of the foot are divided into three area that are hind foot, midfoot and forefoot as shown in Figure 2.2 (Naser & Mahdi, 2016). In hind foot, the first bone is calcaneus bone that also known as largest tarsal bones that made up the heel structure part. The function of this bone is to support the body weight when heel contact happened.

Next is the second bone in the hind foot part that is talus bone. It is the second largest tarsal bones and that function is to join the tibia and fibula bone in order to support the lower leg. For the midfoot part, the bones consist of cuboid, navicular and cuneiform bones. At the lateral side of the foot there is cuboid bone and the shaped of the bone is cuboidal shape as its name. Navicular bone is the second bone of midfoot part. It is placed in the medially and form the upper part of the medial longitudinal arch of the foot.

Lastly is the cuneiform bone that is convexly in shape and it consists of 3 bones which located at the medial, intermediate and lateral of the foot. The shape helps to creates stability to the midfoot. While in the forefoot part, the metatarsals and phalanges bones are numbered I to V starting from medial to lateral. For the big toes, it consist of two phalanges bones that are proximal and distal which is differs from other toes that consist of three phalanges bones, proximal, medial and distal (Riegger, 1802).

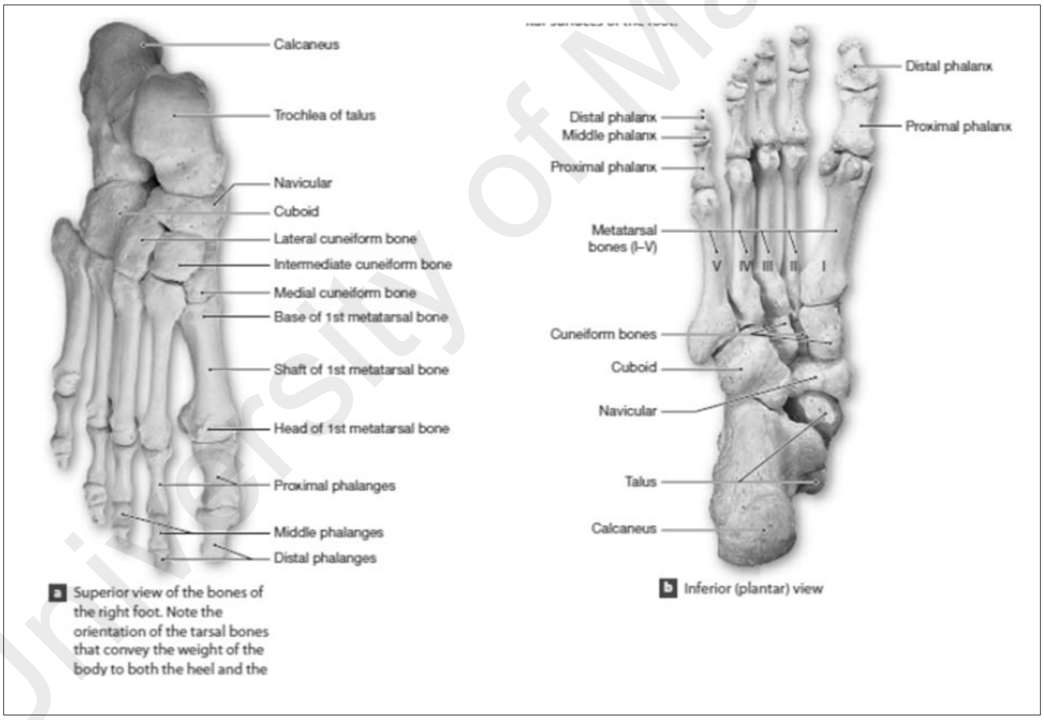


Figure 2.2: The bones in the foot from superior view and inferior view. Retrieved from:(Martini, Timmons, & Tallitsch, 2014)

### 2.2.2 Arches of foot

There are three types of arches in human foot as in Figure 2.3 below. The arches are formed from the link of bones and ligaments in the foot. Their main functions are for mobility and stability of the foot. In terms of mobility, the arches help in shock absorber and help the foot adapts in changes of the terrains. While for the stability, the arches will support in the weight bearing and act as lever to allow the movement of the foot during the gait cycle.

Medial and lateral arches are known as longitudinal arch. For the medial arches, it composes of several bones which are talus, calcaneus, three cuneiforms, and three metatarsal bones. While for the lateral part, it is made up from calcaneus, cuboid, fourth and fifth metatarsal. While for the transverse arch, it was made up from bones that formed wedges shape of the arch  which are three cuneiform bones, cuboid bone and the base of the metatarsal bones (Dawe & Davis, 2011). The structure of the arch is very importance since it can become low arch and high arch depend on the condition of the person foot. The different for the height of the arch will varies the shock absorber of the food during walking. One of the finding suggest that foot that have better shock absorber is normal foot condition with a low arch compare to normal foot with a high arch (Simkin, Leichter, Giladi, Stein, & Milgrom, 1989).

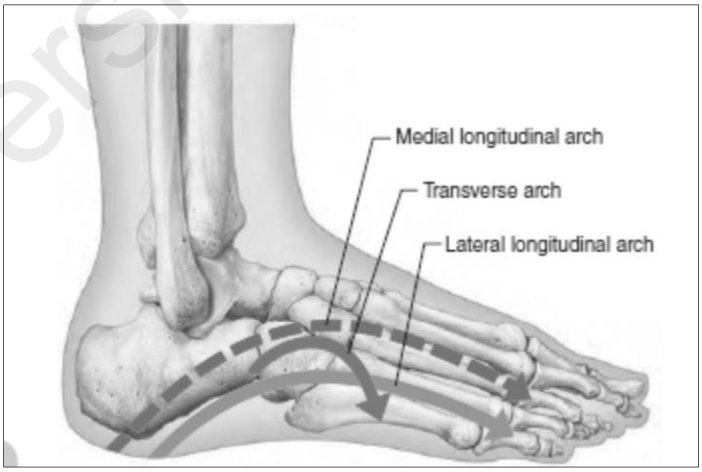


Figure 2.3: Types of arches in foot (Lateral aspect of right foot).
Retrieved from: (Marieb & Hoehn, 2007)

### 2.2.3 Joint of foot

There are 33 joints in the foot structures as shown in Figure 2.4 below. The movement of the foot during gait cycle is due to the motion of the joints. The flexibility and stability of foot during gait cycle were due to motion joint (Dawe & Davis, 2011). There are two main joint in the foot that produce proper movement in which foot can complete a gait cycle.

The first joint is the ankle joint that control the movement that occurs in the sagittal plane which are dorsiflexion and plantar flexion movement of the foot (Hall, 1999). It also functions as hinge joint that has a moving axis of rotation at stance phase of gait cycle. The tendons that present at the ankle joint are Achilles tendon, posterior tibial tendon and the anterior tibial tendon. Each tendon has their own role to support the ankle joint, for example the Achilles tendon will link the calf muscle with calcaneal bone to allow toe lifts movement to happen. While posterior tibial tendon function to support the arch and help foot turn inwards. Lastly, the dorsiflexion movement is supported by the anterior tibia tendon. For the ligaments of the foot, the anterior tibiofibular ligament, posterior tibiofibular ligament and the transverse ligament are function to support the lower end of the leg in which they forms a hinge for the ankle joint.

Next is the subtalar joint that lies below the talus bone, the movement of this joint will depends on the motion of talus on the calcaneus bone. It is also known talocalcaneal joint. The motion produce is a complex twisting motion known as tri-planar motion of the talus bone in the single axis joint thus producing the motion of supination and pronation (Levangie & Norkin, 2011). Others joint in the foot are calcaneocuboid joint, talonavicular joint, naviculcocuneiform joint, tarsometatarsal joints, metatarsophalangeal joint and interphalangeal joints. This joint lies beneath the talus and calcaneus and it lays anterior and posterior facets of the talus articulate with the superior of the calcaneus.

There are 4 talocalcaneal ligaments join the talus and the calcaneus. It is a uniaxial joint that allow supination and pronation movement (Hall, 1999). Study by Phan et al., 2018 shows that tibiotalar and subtalar joint are involve with the translational and rotational movement especially in the initial stance and for the late stance they show significant rotational movement (Phan, Nguyen, Lee, & Koo, 2018). The name of the joints is related to the name of the bones that the joint is connected.

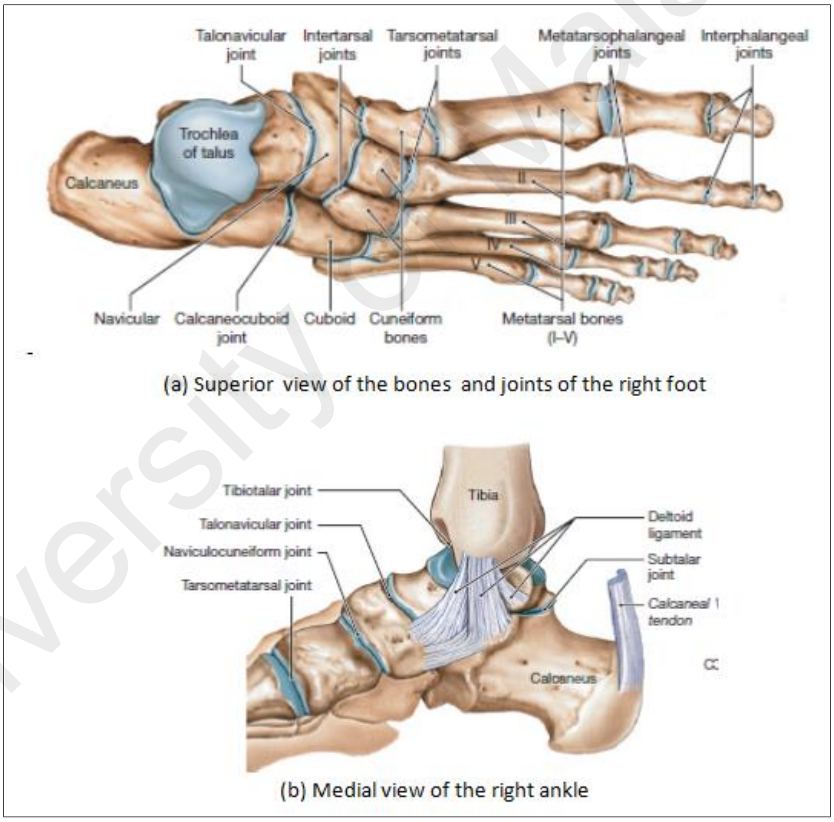


Figure 2.4: The joint of the foot from the superior and medial view.
Retrieved from: (Martini et al., 2014)

### 2.2.4 Biomechanics of foot and ankle joint

By understanding the biomechanics of the foot, we can observe the gait cycle during walking. There are two phase in a Gait cycle, first phase is stance phase which cover 60% of the cycle and second phase is swing phase which cover the remaining 40% as shown in Figure 2.5.

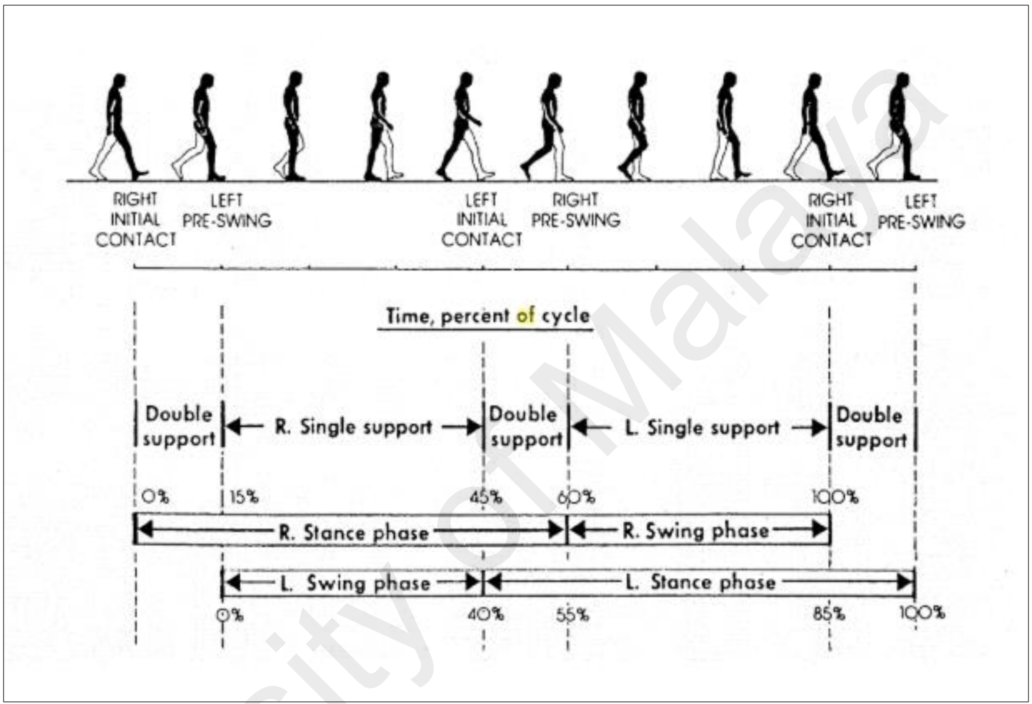


Figure 2.5: The phase in a complete Gait Cycle (%). Retrieved from: (DeLisa, 1998)

The gait cycle firstly starts with the heel make contact with the ground and produce a slight plantar flexion to lift the foot so it does not slap the ground. This will produce high impact of the force and the dorsiflexors contract eccentrically. Then, the stance phase continue with the foot flat where the ankle start to move from plantar flexion to dorsiflexion movement and allow the body to propel forward due to rotation movement of the tibial and fibula around the ankle joint. Then, mid stance phase continue with maximum dorsiflexion movement of the foot. After that, the terminal stance which is the final double stance phase, during this phase the ankle begins plantar flexion to allow the calcaneus lifted from the ground. This movement continues until maximum plantar flexion is achieved at toe-off and enters the swing phase.

The swing phase start with toe off or also known as initial swing where the foot is lifted off the ground accelerates to next phase which is mid swing. During this phase, the leg swings forward to propel the body forward. Lastly, the swing phase complete with terminal swing where the foot decelerates and heel start to make contact with the ground. During swing phase, the ankle is in stay in dorsiflexion before returning to slight plantar flexion at heel strike. This action will allow the foot to clear the ground and stabilize the body from falling. This movement follows with 15 degree of eversion and inversion of the subtalar joint. In most cases, at heel-strike, inversion of the calcaneus is demonstrated, and advances to eversion during mid-stance phase, enabling the heel to rise and propel into swing phase (Brockett & Chapman, 2016).

In addition, pronation and supination provide the basis for adequate momentum and balance for biomechanics of the ankle as show in Figure. 2.6 below. The movement starts with initial contact where the foot moves slightly supinate as the foot go through initial contact phase. Moving to foot flat phase, the force is absorbed by the pronation at the ankle joint and flexion movement of the knee joint. The movement of subtalar joint from supination to pronation will help the foot to move forward especially on uneven terrains. Then, move to terminal stance, where the foot is move to the supination movement and acts as a fixed lever and help in push off movement. This supinated motion also is seen at the subtalar joint, providing for an efficient and strong support at toe-off (Charrette & Overpronation).

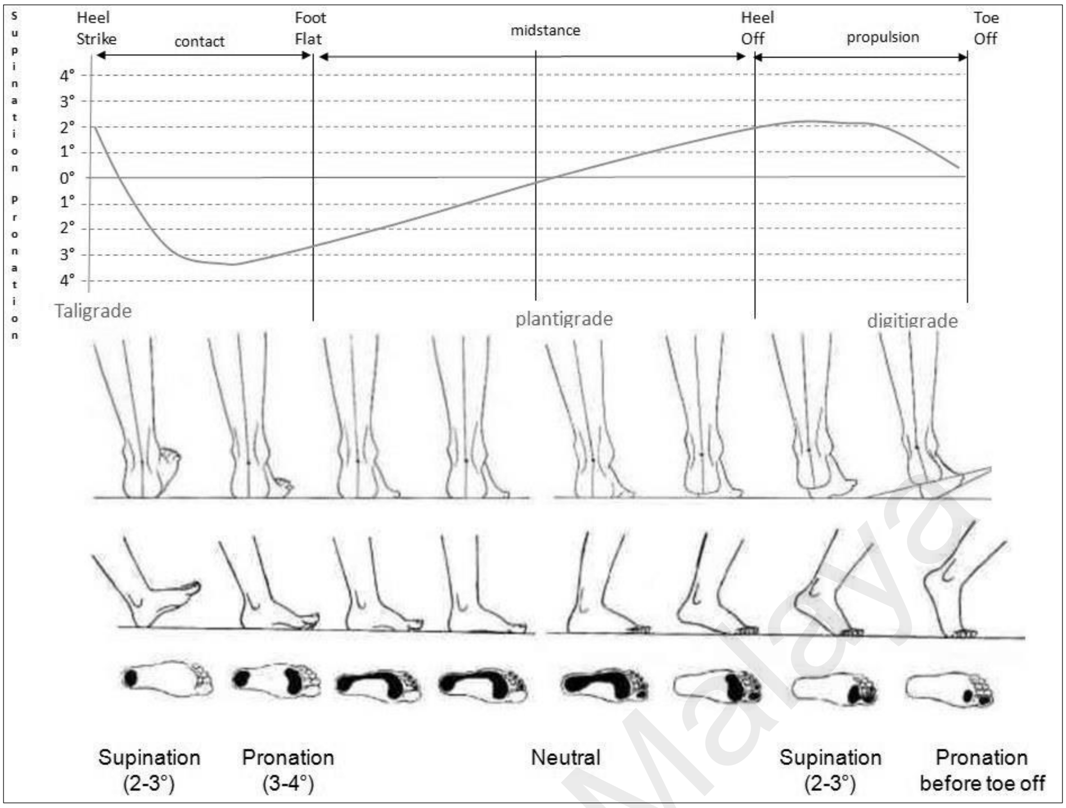


Figure. 2.6: Frontal and sagittal view of the foot movement during the gait cycle. (Adapted from: https://sme-chinoises-euronext.typepad.fr/artbot/2014/09/a-study-of-walking-in-order-to-design-a-biped-robot.html/)

## 2.3 Over-pronation

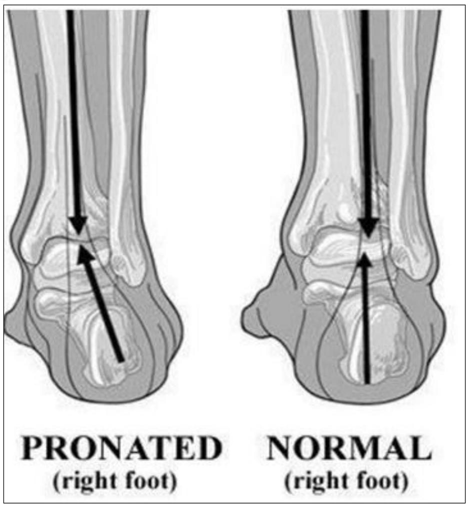


Figure 2.7: Appearance of pronation foot (right foot). Retrieved from:(Snook, 2001)

Pronation is define as the inward foot rotation movement as shown in Figure 2.7 above. The movement is inward and downward of the medial bones in the mid-tarsal region which allow the foot to come down on its inner margin during walking for shock absorption. This movement also present during walking and running. This movement is known as the toe-off portion of the gait cycle since it will allow rolling off the big toe. Pronation also helps in the initial contact (stance phase) of the gait cycle in which the foot rolling inward motion just after it lands on the ground. Pronation is important for stabilization in standing and walking but excessive range of this motion or over pronation can lead to many other problems.


**Fi**gure 2.8: Appearance of the foot with over-pronation (Excessive degree of subtalar joint angle) and flat foot (Low arch). Retrieved from: (Giannini, Faldini, Cadossi, Luciani, & Pagkrati, 2012)

Figure 2.8 on the other hand shows the over-pronation of the foot. It is define as dysfunctional movement in which the foot has to turn in excessively from its neutral line. Therefore it can cause the majority of the body weight to fall on the medial aspect of the foot. In this case, the big toe and the second-toe of the foot shoulder the burden of stabilizing the body during toe-off instead of the ball of the foot. This results in reduced cushioning capabilities as well as reduced stability. One of the methods to observe over-pronation condition is by measuring the calcaneal eversion or rear foot angle (RA). The RA must be equals to or exceeds 10° and the longitudinal arch angle was less than 134° measured during standing (Genova & Gross, 2000).

Over-pronation can be measure by looking at the subtalar joint angle of the foot in the frontal plane, posteriorly since it is the combination of eversion, abduction and dorsiflexion of the foot. The range of motion that usually consider to be over-pronation is when it exceeds 5° of angle from the subtalar neutral position when standing and exceeds 15° of angle when walking (heel strike and push off) (Kernozek & Ricard, 1990). This excessively pronation is always associated with flat foot or low arch foot in which the arches of the foot collapse and form a postural deformity in which the entire sole of the foot will be near or total contact to the ground. Flat foot can vary in their degree of collapsing, depending on it degree of over pronation.

Over-pronation is not only causing the alignment of the foot to be away from its neutral position and the foot arch to collapse but it also effects the alignment of the body and leg entirely as in Figure 2.9. It is because the low arch will pulls the heel bone in and will cause the leg and hip to rotate inward and anteriorly tilt the pelvis. The misalignment of the leg due to over-pronation that cause by subtalar instability can be seen by looking at the posterior frontal plane of the leg, and comparing the joint of the leg and the bone alignment with normal person without any subtalar instability.

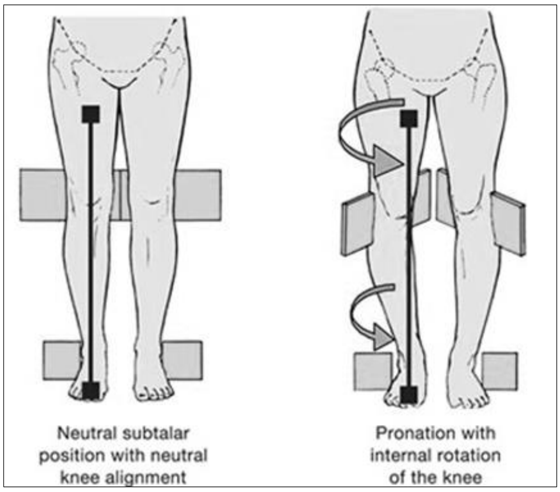


Figure 2.9: Foot and leg misalignment due to over-pronation cause by the subtalar instability. Retrieved from: http://blackwoodphysiosportsandspinal.com.au/hip-knee-ankle-pain/

In normal person that has a normal range of pronation, the outside part of the heel will make initial contact with the ground when walking. When the foot landed on the ground, the foot landed on the ground, the foot arch will flatten out, as the foot attempts to reduce the impact of the landing. When the arch flattens the ankle naturally will roll inward about 10° to 15 ° from the natural position, and it will support the body weight without any problem. However, in person with over-pronation feet condition, the foot rolls inward more than the ideal 15° of rolling as in Figure 2.10 (Kernozek & Ricard, 1990).

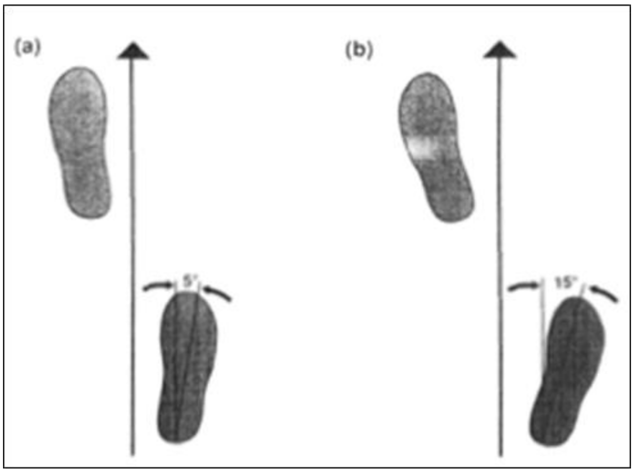


Figure 2.10: Foot placement is the angle if orientation of the foot relative to the direction of travel. Retrieved from: (Kernozek & Ricard, 1990)

This will cause the foot and ankle has more problems stabilizing the body, and shock absorption will not be efficient. At the end of the gait cycle (push off), the front of the foot pushes off the ground using mainly the big toe and second toe, which lead to an excessive pressure being putting into the 1st metatarsal head, which can cause ulcer to the skin as in Figure 2.11. This also cause the foot and ankle to be unstable since the shock from the foot impact does not spread evenly throughout the foot. It is common even for people who pronate normally to have some angle between the foot and the ankle, but not to the extent seen in those who over pronate (Hintermann & Nigg, 1998).

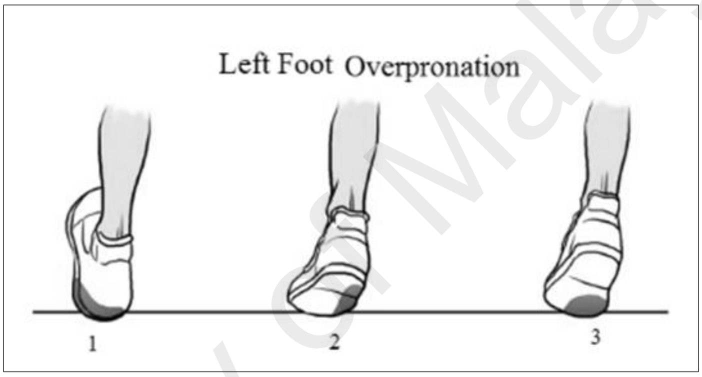


Figure 2.11: Over-pronation walking pattern. Retrieved from: https://www.menshealth.com.sg/running/pronation-runners-guide/

Over-pronation issue or problem can also be identifying by looking at the shoes condition. Person with over-pronation will have a wear on the inside of the shoes due to more pressure is applied at the medial side of the foot. For this subtopic, it can be concluded that over-pronation feet condition can cause the joint movement to be away from its natural position (eversion) and causes the gait deviation and misalignment of the body to happen which can lead to joint instability.

## 2.4 Over-supination

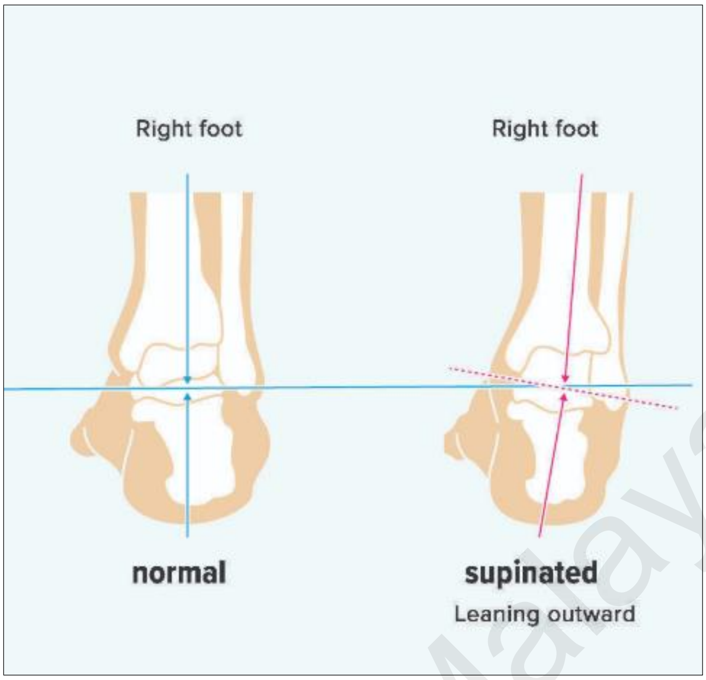


Figure 2.12: Appearance of supination of foot (right foot). Retrieved from: https://www.healthline.com/health/bone-health/whats-the-difference-between-supination-and-pronation#the-foot

Supination as in Figure 2.12 is the opposite movement of pronation. It is the motion of foot rotation where the medial bones in the mid-tarsal region of the foot outward and upward so that the foot rolls outward with an elevated arch to propel the body forward during walking. The term is usually used in connection with over-supination, which means there is an excessive roll out of the foot.

Over-supination is the condition in which the foot does not pronate much as it rolls out away from the body middle line and the occurrence of supination in excess or supination that occurs longer than it should during certain phases of the gait cycle. The angle of supination that consider to be over supination is when it exceeds 5° angle from the subtalar neutral position when standing and 10° angle when walking (Gentili, Masih, Yao, & Seeger, 1996) and longitudinal arch angle (LAA) above 152°(Lundberg, 1989).

Over-supination also falls outside of functional parameters, and are a combined inversion, adduction and plantar flexion of the foot. Common signs of supination are high arches or also known as pes cavus. High arch is opposite with low arch it which the person with high arch will have a hallow space below their foot or arch. There will be decrease in the capacity of the foot for shock absorption if the foot does not pronate enough due to arch that not flatten our sufficiently. As shown in Figure 2.13, the external rotation of the lower limb and knee happened due to misalignment of the leg and foot since the weight bearing tends to focus on the outside border of the foot.

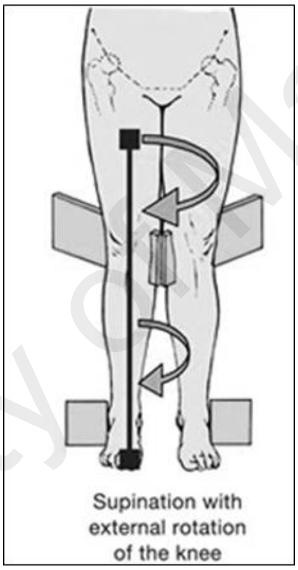


Figure 2.13: Misalignment of the foot due to over supination. Retrieved from: http://blackwoodphysiosportsandspinal.com.au/hip-knee-ankle-pain/

When walking, there will be an inward movement of the foot occurs at less than 10° of angle when the outside part of the heel makes initial contact with the ground. From Figure 2.14 below there is lateral loading of the foot that happened in entire stance phase of the gait due to large transmission of shock that happened on the lower leg because of no normal pronation action happened. The excessive increase in the angle will cause the force of impact to be concentrated on a smaller area of the foot (the outside part), and are not distributed as efficiently. In the push off phase, the smaller toes on the outside of the foot do the most of the work and there will be an addition pressure to the area. This excessive force then has a flow- on effect to the rest of the muscles in the leg.

In term of the shoes condition, over-supination patient will show wear out outside of their shoes and heels. It happened because many of these people land on the outer portions of their feet and then have a roll excessively toward the midline to launch off their big toe to take a step. For this subtopic, it can be concluded that over-supination due to subtalar joint instability had because the joint movement to be away from us natural position (inversion) and causes the gait deviation and misalignment of body to happen.

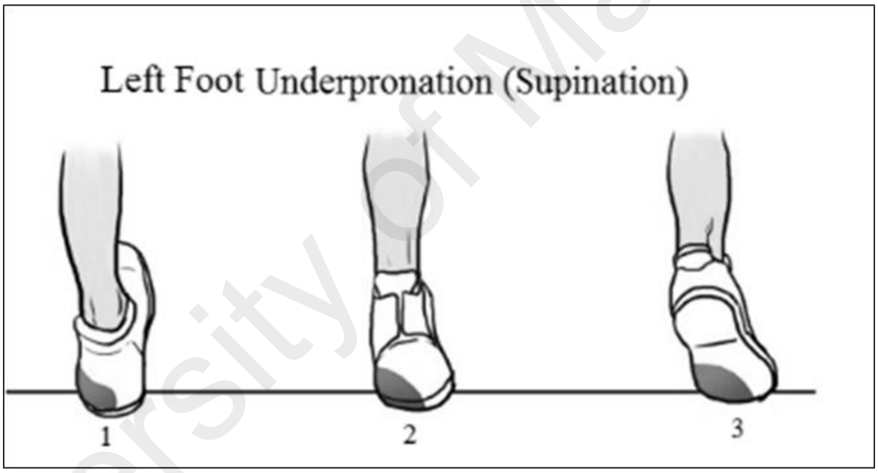


Figure 2.14: Over-supination walking pattern. Retrieved from: https://www.menshealth.com.sg/running/pronation-runners-guide/

## 2.5 Biomechanics evaluation of gait analysis

Biomechanics evaluation is the most important part to study the gait analysis of the subject so that we can know the gait alterations in subjects with over-pronation and over-supination condition. From the previous study there are many ways and instrument used to analyze the gait cycle. Study by (Allet et al., 2009) used different walking surface which is stone, grass and Physilog 1 system tar to assesses the subject. Other study by (Paul, Ellis, Leese, McFadyen, & McMurray, 2009) used GAITRite Walkway in single and dual task to analyze the gait parameters. Next is (Ko, Stenholm, Chia, Simonsick, & Ferrucci, 2011) that used Vicon 3D motion capture system with 10 digital camera operating at 60Hz sampling frequency was used for their study. A recent paper in 2015 measure the cadence by walking on 11m pathway called Walk Ratio with self-selected and maximal speed (Camargo et al., 2015).

Therefore, after comparing all the method, the best and most suitable method to study about the biomechanics of individual with over-pronation and over-supination feet during walking is by using Vicon 3D motion capture system (Jenkyn, Anas, & Nichol, 2009).

### 2.5.1 Vicon$^{TM}$ Nexus 1.3 3D Motion Capture System

Vicon$^{TM}$ 3D motion capture system is a video-based motion analysis and the movement was captured by the five infrared cameras with sampling at 100 frame rate per second. The concept of this motion capture was by reflect the infra-red from the camera to the passive reflective sphere marker then, the marker will reflect back the signal to the camera and the movement was recorded. All the kinematic parameters such as angle of the joint will be calculated between each segment of the marker. 16 passive reflective sphere markers of 15mm diameter were attached to the subjects lower limb, the position of the marker was follow the specific anatomical landmarks for the lower limb part (Plug-In Gait Marker Set, Vicon Peak, Oxford, UK) follow the Helen Hayes market set placement as shown in Appendix C. While the kinetic data was determined using two rectangular metal force plates embedded in the floor of the walkway (Abu Osman & Mohd Ismail, 2009) .

The Vicon software enables the connection between to the infrared camera and the system so that the recording and calculation can be done. Before starting the experiment, the first thing to do was calibration of the system. The calibration of the system was done to define loco (joint) and global (lab) coordinate system of the experimental space. Proper distance was prepared for the subjects to walk in their normal speed and during the walking they will pass through the embedded force plates on the floor so that the ground reaction force, GRF can be calculate.

## 2.6 Diagnosis and treatment

Subtalar and ankle instability has been in focus during these recent years as one of the possible factor behind chronic functional instability of the foot. The exact aetiology and the true incidence of subtalar ligament injuries remain unknown. Most subtalar ligamentous injuries probably occur in combination with injuries of the talotibial articulation, subtalar instability can have the characteristics of chronic lateral instability or recurrent ankle sprains (Karlsson, Eriksson, Bergsten, Rudholm, & Swärd, 1997).

The over-pronation and over-supination foot condition can lead to joint instability if no proper treatment is done. Over-pronation of the foot is characterized by a fallen arch structure, thus changing propulsive mechanics, elevating the demand on supporting structures including the plantar fascia, and modifying the load distributions on the plantar surface of the foot, while over-supination can cause lateral ankle sprains. The failure of the lateral aspect of the ankle particularly the peroneus muscle to prevent excessive supination affects ankle instability(Fong et al., 2009)

Foot-ankle joint instability is a condition that is characterized by the looseness and/or giving away the joint and it is usually associated with ankle instability. The loosening of the joint that caused by the injury of the ligament of the foot-ankle joint and sometimes happens due to the previous ankle injury that goes without treatment. There are also cases, in which the joint instability happens since birth (congenital), such as shallow or malformed joint surfaces. It is more common to see adults present with pain and problems associated with joint instability, but in the case of the congenital the condition may be present to children. Pain may be felt in soft spot on the outside of the ankle (Amendola, Lee, Saltzman, & Suh, 2007).

The major problem consequences of having an unstable subtalar and ankle joint is that the foot will be in the position and motion of over pronation and over supination, which lead to the other problem or deformities which are, the abnormality of the foot arch, the misalignment of the foot and leg, gait deviation and bad shoes condition. Thus, in this study, the focus will be on the observing and analyzing the joint instability in individual with over-pronation and over-supination foot since these two conditions related to each other.

Subtalar instability can be suggested by the subject feeling of the ankle instability, easy "rolling over", and a need to look at the ground constantly when walking (Barg et al., 2012). It is a developing issue that appears to bring about a part of interminable hind foot unsteadiness. It can be seen as isolated problem, or more commonly, in combination with ankle instability. There seems to be many injury mechanisms, most of which seem to involve supination of the hind foot, and all seem to attenuate the lateral ligaments of the ankle and subtalar joints. As the condition advances and extra sprains happen as a change's consequence in subtalar joint mechanics, the remaining ligaments become attenuated. There are many methods described to diagnose subtalar instability, but no conclusive test has been devised (Keefe & Haddad, 2002).

Based on the research, the best ways to determine and diagnosis of the instability of the foot and ankle joint is by measuring the joint angle in sagittal plane, looking at the arches of the foot as well as the alignment of the foot and leg. By comparing the medial arch of the foot, whether it is low arch or high arch and relate it to the degree of misalignment of the foot in the frontal plane, we will be able to suggest the stability of the subtalar joint.

As with other foot injuries, many subjects improve with conservative measures. There include an early treatment that involves the use of ice and medication to help reduce pain and inflammation in the cases of subtalar instability due to trauma. Elevation and compression bandage mat also help reduce inflammation. Common foot and ankle presentations of joint instability are posterior tibial tendonitis, anterior tibial tendonitis, plantar fasciitis and forefoot pain commonly associated with lesser metatarsal head overload. Initial treatment for these entities includes improved shoe gear, supportive devices and taping and bracing techniques.

Often, the problems of these subjects require more permanent support and control and custom orthotics become necessary. It helps in immobilize the joint and allow or healing. After immobilization, it is important to perform strengthening and stretching exercises to help regain strength and a full range of motion. It also believes that orthotic footwear able to correct deformities and accommodate joint movement in cases where the subtalar joint instability is mild or severe. Therefore it is importance to detect the over-pronation and over-supination because these conditions can lead to injuries such as ankle sprains, shin splints, Achilles tendinitis and others. By early detect this condition, we can provide guideline for injury prevention not only for athletes but also foe the publics (Eizentals, Katashev, Okss, Pavare, & Balcuna, 2019).

### 2.6.1 Classification method of Over-pronation and Over-supination group

The most proper method to classify the subjects into over-pronation, over-supination and normal group is by using the foot posture index (FPI). FPI was chosen because it is one of the best methods to analyze the foot posture and it was proved clinically by many studies before (Redmond, Crane, & Menz, 2008). The method to do this FPI was by assessing the subject during weight bearing and non-weight bearing activity. This test is to qualify the degree to which foot is pronated, neutral or supinated. The test was done under supervision of prosthetist and orthotist category 2.

6 criterion-based observation of rear foot and forefoot where used that were talar head palpation, curvature at the lateral malleoli, inversion/eversion of the calcaneus, talonavicular bulging, medial longitudinal arch and abduction/adduction of the forefoot on the rear foot as shown in Figure 2.15. All the criteria were evaluate using scale of (0 for neutral – 2 for clear signs of supination and +2 for clear signs of pronation) (Lee, Kim, Jeong, Kwon, & Jeong, 2015). All the subjects shows FPI more than -7 were selected for the test. The foot posture index form used in this study is show in Appendix B.

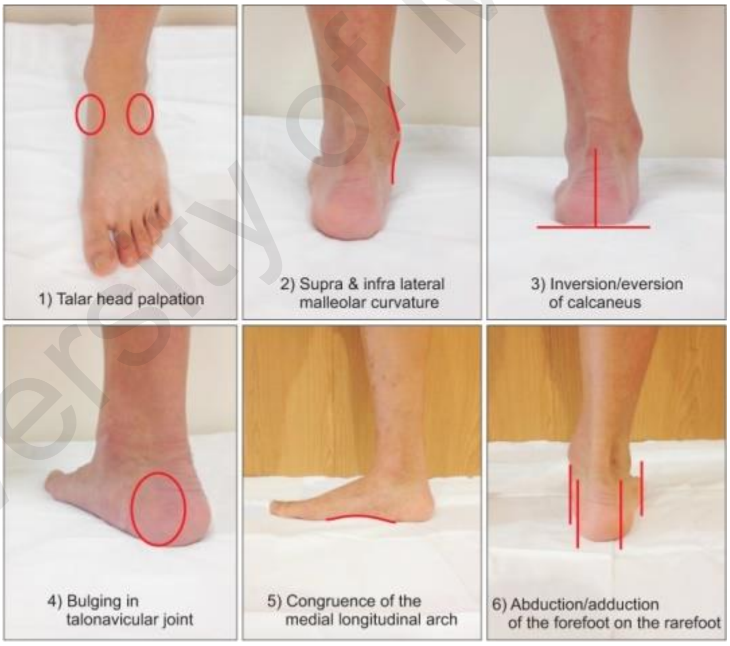


Figure 2.15: The Foot Posture Index Criteria. Retrieved from: (Oleksy, Mika, Łukomska-Górny, Marchewka, & Machines, 2010)

Other method is by using navicular drop test that used to evaluate the function of the medial longitudinal arch. The test is done by assess the position of talus and over-pronation of forefoot. The navicular drop test is a simple and suitable parameter for clinical assessment for foot eversion and rear foot movement. It is defined as the distance of the navicular tuberosity moves in standing as the subtalar joint is allowed to move from neutral to relaxed position. The method to this test is by measure the distance from the ground to the tuberosity when the patient stand still without weight bearing and with weight bearing position as shown in Figure 2.16 below. The measure difference more than 1 cm is classified as over-pronation feet condition while if less than 1cm it is over-supination feet condition.

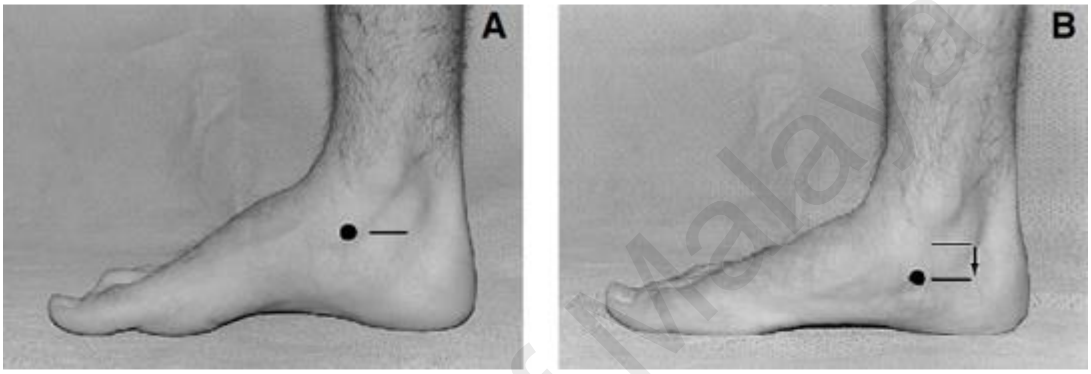


Figure 2.16: Navicular Drop Test. Retrieved from: (Lange, Chipchase, & Evans, 2004)

## 2.7 Summary of Literature Review

Table 2.1: Summary of Literature Review

| No. | AUTHORS | JOURNAL | SUBJECTS | OBJECTIVE | PROTOCAL | OUTCOME MEASURE | FINDING |
|---|---|---|---|---|---|---|---|
| 1. | (Shih et al., 2011) | Application of wedged foot orthosis effectively reduces pain in runners with pronated foot: a randomized clinical study | 24 runners (18 males and 6 females) | To examine the effects of foot orthosis intervention during a 60 minute running test in pronated-foot runners with overuse knee or foot pain during running. | Do 60 minute running test on treadmill.<br>Treatment group (n=12) received a flat insole with 5° rear foot posting.<br>Control group (n=12) received a non-wedged flat insole. | Pain intensity and pain onset time during the test.<br>Pain intensity (recorded using the visual analogue scale [VAS 0 to 100] | Pain incidence reduces in the treatment group but not in the control group.<br>The rear foot medially-wedge insole was a useful intervention for preventing or reducing painful knee or foot symptoms during running in runners with pronated foot. |
| 2. | (Mitchell et al., 2008) | Biomechanics of ankle instability. Part 1 : Reaction time to stimulated ankle sprain | 19 males<br>With history of unilateral ankle sprain and functional ankle instability (Hisham, Nazri, Madete, Herawati, & Mahmud)<br>19 males as control | To test that ankle with functional instability will demonstrate slower muscular reaction times than their contralateral stable ankle (SA) and stable healthy control to a stimulated non- | 2 group :<br>-Functional ankle instability (Hisham et al.)<br>-Control group<br>The EMG data is recorded from both limbs.<br>Subject carried out prescribed movement 3 times as warm up:<br>Plantar flexion, dorsiflexion, inversion, eversion.<br>Subject stood barefoot on the | The reaction times of the peroneus longus, peroneus brevis and tibialis anterior in unstable ankle.<br>Used 10 channels with $Myodat^{TM}$ 5.0 software:<br>4 recorded the EMG activity of 4 muscle on support limb,<br>4 recorded 4 muscles | Results demonstrate a deficit (slower reaction time) in ankle with FAI when acting to support and when exposed to a stimulated sprain compared to stable health control.<br>As a slower result of the slower reaction times, acting to support the unstable ankle may put |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | pathological ankle sprain mechanism.<br>To investigate whether muscular activity magnitude played a moderate role in response of the limb to stimulated ankle sprain. | platform with feet shoulder with apart in a relaxed stance and body weight spread evenly between both feet.<br>1 limb is randomly exposed to the unilateral stimulated ankle sprain (USAS)<br>Each limb was exposed 6 times to the USAS in random order.<br>The EMG data activity is recorded. | on limb exposed to the USAS,<br>1 recorded USAS onset pulse. | the contralateral stable ankle at an increased risk of ankle sprain. |
| 3. | (Hagen, Sanchez-Bergmann, Seidel, & Lahner, 2015) | Angle-torque relationship of the subtalar pronators and supinator in younger and elderly males and females | 30 younger (15M and 15 F)<br>30 elderly (15M and 15 F)<br>-no contraindication to resistive exercise, no orthopaedic, cardiac or visual problems) | To investigate the isometric angle-dependent pronator and supinator strength capacity in younger and older males and females. | Maximum isometric strength tests of the pronators and supinator of dominant foot were administered.<br>The navicular drop test was performed to determine the characteristics of the medial longitudinal foot arch.<br>Subtalar strength testing performed using a specific foot apparatus mounted on a wooden based plate (shoe is attach to the machine)<br>Strength testing is done in 5 anatomical positions within the subtalar movement plane:<br>-24° and 8° pronated position. | Range of subtalar motion<br>(the axis of the foot apparatus corresponding to the subtalar joint axis)<br>Angle-torque relationship<br>-peak pronator torque (PPT)<br>-peak supinator torque (PST)<br>Used ANOVA with repeated measures comprising joint angle and the independent factor 'age' and 'sex' was applied to identify | The pronator and supinator muscle strength across subtalar range of motion, age and sex related differences in subtalar strength profile and range of motion has to be considered as both effect the strength curves and PSR.<br>Younger females have higher pronator strength capacity in the most pronated joint angle- due to greater subtalar range of motion. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | -8°, 24° and 40° supinated position.<br>Strength testing (leg dominant) | differences in angle-torque relationship and the relative strength curves. | |
| 4. | (Doherty et al., 2016) | Coordination and symmetry patterns during the drop vertical jump in people with chronic ankle instability and lateral ankle sprain copers | 70 subjects :<br>28 (chronic ankle instability, CAI)<br>42 (lateral ankle sprains , LAS copers) | To identify the coping movement and motor control patterns of lateral ankle sprain (LAS Copers) in comparison with individuals with chronic ankle instability (CAI) during drop vertical jump task(DVJ) | Attend the testing laboratory to complete a DVJ task.<br>Subjects were first instrumented with 22 infrared markers as part of the bilateral lower limb gait setup.<br>Required 3 repetitions of a DVJ task following a practice period.<br>Subject began standing barefoot a top of 0.4m platform with their hand on their hips and their feet approximately shoulder width apart.<br>Instructed to drop down from the raised platform without any vertical launch and land on both feet simultaneously (phase 1)<br>Then, immediately executed a maximal vertical jump upon contact with the force plates (phase 2) | 3-D kinematic and sagittal-lane kinetic profiles were plotted for the lower extremity joint of both limb.<br>The rate of impact modulation relative to body weight both phases of the DVJ also were determined. | Subject with CAI displayed hip-centred changes in movement and motor pattern during a DVJ task compared with LAS copers.<br>Subjects with CAI displayed significant increases in hip flexion on their "involved" limb during phase 1 of the DVJ (20° vs. 18°) and bilaterally during phase 2 ( 15° vs. 10°) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5. | (Kakihana et al., 2005) | Effect of a lateral wedge on joint moments during gait in subjects with recurrent ankle sprain | 50 subjects (males)<br>-25 unstable lateral ankle<br>-25 healthy controls<br>Test using :<br>-anterior drawer test<br>-clinical talar tilt test. | To assess the effects of wearing a 6° wedged insole on the subtalar and knee joint movements during gait for persons with an unstable lateral ankle. | 1) Reflective markers (20mm in diameter) were placed over body landmarks to minimize skin movement.<br>2) Subject was instructed to stand barefoot for 5 sec to establish the relationship among the markers for the subject's initial anatomical position.<br>3) Standing trials, they were instructed to stand with knees as fully extended as possible, the ankle at 0° dorsiflexion and a comfortable degree of toe-out.<br>4) Walking trial, wedge is attached to the subject's feet and they were asked to walk at self-selected waling cadences. | -3D segment rigid link model that will be used to describe the motion of the lower extremities in frontal plane.<br>-Moment acting about each joint was calculated using an inverse dynamic algorithm and expressed as external movement.<br>-Valgus movement arm of the subtalar joint.<br>-COP location during stance phase parallel to the subtalar joint axis.<br>-Joint movement, vertical and mediolateral | In comparison with the control wedge (0°), the lateral wedge (6°) significantly increased the subtalar joint valgus movement and reduced the knee joint varus moment during gait. These result the lateral wedge also correlated with a laterally shifted location of the CoP during stance phase. |
| 6. | (Kosonen, Kulmala, Müller, & Avela, 2017) | Effects of medially posted insoles on foot and lower limb mechanics across walking and | 11 over-pronating men with normal (NORM) and Medially posted insole (MPI) insole during walking and | To investigate the effects of MPI on walking and running mechanics in over pronating men, using a multi-segments | 1)insole preparation was based on heated orthotic blanks (using moulding pillow, subject stepped on it, moulding pillows reacted to the pressure and heat)<br>2)subjects were instructed to used their MPI every day (for | Kinematic and kinetic data was analyse using vicon plug-in gait model.<br>-marker trajectories and GRF data.<br>-lower limb joint moments in the sagittal | The present study showed that MPI primarily affected the fore foot motion by reducing the peak eversion movement across walking and running when compared |

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|---|---|---|---|---|---|---|---|
| | | running in over pronating men | running.<br>Over pronation criteria was a navicular drop value over 10mm (measure as the distance between navicular height in barefoot standing with the subtalar joint in neutral position and in relaxed stance) | foot model. | approximately 2 weeks before biomechanical walking and running measurement to familiarize themselves)<br>3)Biomechanical data collection:<br>-attach to 28 retro-reflective markers (using plug-in gait and oxford foot model)<br>-subjects 1st performed walking at a self-selected speed and then performed running trials at a target speed of 4.0 m/s.<br>-3 to 6 walking and running trials.<br>-data were collected using the same running shoes with normal insoles of the shoes (NORM) and with MPI in random order. | and frontal planes were calculated via inverse dynamic about an orthogonal axis system. | to NORM.<br>Kinetic responses (alteration in COP path and frontal plane moments) to MPI were more pronounced in running than walking. |
| 7. | (Aguilar, Abián-Vicén, Halstead, & Gijon-Nogueron, 2016) | Effectiveness of neuromuscular taping on pronated foot posture and walking plantar | 70 runner:<br>KT (n=49)<br>Sham KT (n=24)<br>KT = kinesiotaping | To determine the effect kinesiotaping (KT) versus sham kinesiotaping (sham KT) in the repositioning of pronated feet | 1) Examine the short-term effect of KT, no follow-up was taken.<br>2)Continues running 45 min<br>3) Measure FPI and plantar pressure using bio foot.<br>4) Pressure measurement was taken while walking along a | The pressure data was tested for normally by using the Kalmogorov-smirnov test.<br>Pressure time integral (PTI KPa/s) at heel strike and toe off.<br>-pressure outcome | This study suggest that KT can modify static pronated foot posture in amateur runners toward a more neutral position after a short run (45 min duration)<br>-kineostaping appears to |

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| | | pressures in amateur runners. | | after a short running. | 20 m line, in a single direction and at a self-selected walking speed.<br>5) This (4) procedure followed for both walking trials.<br>6) All subjects are asked to walk normally without informing the subjects to encourage natural gait.<br>7)6 steps recorded and repeated 3 times.<br>8) Kinesiotaping was applied according to procedure recommended; standard 5 cm black irisana © tape was used.<br>9) Sham KT was applied.<br>10) Both screening and intervention assessment were taken under 3 days apart under same condition.<br>11) Repeat same procedure as 1st say, continuous running 45 min.<br>12) Repeat both FPI and plantar pressure test after remove the kinesiotaping. | were calculated as the mean of 3 walking trials.<br>- Confidence interval (CI) was calculated. | have very little effect in the change of foot pressures, in contrast the sham KT technique (without tension) appeared to have a greater effect by increasing pressure time integral, in mid foot and fore foot region in terminal stance. |
| 8. | (Ringleb et al., 2011) | Effects of lateral | 8 fresh-frozen cadaveric lower | To create a cadaver model of | 1) For each condition (intact ATFL and Cut ATFL), 2 | Data collected using Polhemus and the | The ATFL and CFL contributed to ankle |

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| | | ligament sectioning on the stability of the ankle and subtalar joint | extremities cut at the mid-shank (5 left leg and 3 right leg) | the aforementioned injury mechanism of subtalar joint instability.<br>To investigate the effects of this mechanism on subtalar joint under multiple loading condition. | trials of data were collected throughout the range of motion in plantar flexion/ dorsiflexion, inversion/eversion, internal/external rotation, supination/pronation, AP drawer and inversion/eversion while ankle was held in dorsiflexion.<br>Supination: the combination of plantar flexion, inversion and internal rotation.<br>Pronation is the combination of dorsiflexion, eversion and external rotation. | motion monitor software.<br>Used MATLAB and SPSS (ANOVA).<br>Maximum motion of subtalar joint, ankle joint and motion of the hind foot with ligaments serially sectioned. | instability. ATFL also contributed to ankle stability during internal rotation.<br>Interosseous ligament was the major ligament contributing to subtalar joint instability. |
| 9. | (Ntousis, Mandalidis, Chronopoulos, & Athanasopoulos, 2013) | EMG activation of trunk and upper limb muscles follow experimentally- induced over pronation and over supination of the feet in | 28 healthy individuals (11 males and 17 females)<br>-without skeletal deformity, LLD, over pronated or over supinated feet or excessive pelvic indication. | To examine whether such foot deformity affects the activity of muscles that act on the trunk and upper limb. | 1) Bilateral EMG recordings of latissimus dorsi, pectorialis major and rectus abdominis were undertaken for 30 s with each subject in relaxed standing position.<br>2) At 5° and 10 ° bilateral or unilateral over pronation or over supination of the foot on the dominant side using wooden wedge shape blocks.<br>3) Recorded EMG activity was normalised based on | -Means and standard deviation of the anthropometric data and the calcaneal angle differences that resulted from the use of the wedge-shaped block.<br>-3 muscles did not demonstrate any statistically significant changes of their EMG recordings between the | Neither bilateral or nor unilateral over pronation/ over supination of the feet induced a significant alteration of the EMG activity of the latissimus dorsi/pectoris major and rectus abdominis on either dominant or non-dominant side.<br>Above finding suggest that, the absence of the major structural |

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| | | quiet standing. | | | EMG activity produced by the muscles under investigation during maximum isometric voluntary contraction.<br>4) EMG activity of muscles under investigation was recorded bilaterally for 30 s with each subject quiet standing:<br>a) Both feet flat on the floor.<br>b) With both feet in the 5° or 10 ° of pronation or supination.<br>c) With dominant foot in 5 ° or 10 ° pronation or supination and the Cora lateral foot flat. | various positions of the feet on both dominant and non-dominant sides. | deformity or unilateral foot over pronation or over supination does not affect the EMG activity of muscle that act on the trunk and upper limb in quiet standing. |
| 10. | (Golightly, Hannan, Dufour, Hillstrom, & Jordan, 2014) | Foot disorders associated with over pronated and over supinated foot function: The Johnston Country Osteoarthritis Project. | n=1466 (67.2 % women and 29.5 % African American, mean age 68.5 y/o) | To determine whether specific musculoskeletal foot disorders were associate with over pronated and over supinated feet in a large, community-based cohort of Caucasian and | Foot disorders were identified with a validated assessment tool, each foot categorizes as over pronated, over supinated. (Referent using the centre of pressure excursion index (PEI) from foot pressure scans during normal-placed walking.<br>1) Examine foot function:<br>-plantar pressure data were collected using Tekscan | Foot pressure and CPEI data | Foot function is associated with special foot disorder in this bi-racial, community based study.<br>Foot function was related to hallux valgus and overlapping toes, especially among obese. |

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| | | | | African American men and women who were normal weight, over weight and obese.<br>To examine whether relationship of foot disorder and foot function differed by race and body mass index category. | matscan system.<br>-centre of PEI, a measure calculated from the walking pressure scan data, measures dynamic foot pronation and supination. CPEI value is determine by :<br>a) Drawing a line from 1st and last centre of pressure data points of the foot.<br>b) Measuring the distance this line and the centre of pressure in anterior third of foot.<br>2) Dividing the distance between line and centre of pressure by forefoot width. | | |
| 11. | (Cain, Nicholson, Adams, & Burns, 2007) | Foot morphology and foot/ankle injury in indoor football | 76 adolescent males futsal player (12 to 17 y/o)<br>-30 players in 12-13 y/o<br>-25 in 14-15y/o<br>-21 in 16-17 y/o (Were asymptomatic for foot ankle pain. Subjects were required to | To determine whether foot posture, as measurement by the FPR-6, was associated with coach-rated ability levels and reports of ankle/foot overuse injury in adolescent male futsal players. | 1) Demographic and player profile detail were collected in questionnaire, height and weight were measured.<br>2) Subject stood in their comfortable angle and base of gait, with their comfortable angle and base of gait, with their arms by their sides and looking straight ahead to assess the FPI-6.<br>3) Only one foot of each subject (dominant leg) was | 6 constituent measures required to assess overall foot posture are as follows:<br>1)Talar head palpation<br>2)curves above and below lateral malleoli<br>3)inversion/eversion of the calcaneus<br>4)bulge in the region of the talonavicular joint<br>5) Congruence of the | The FPI-6 measure of foot morphology was found to have a good inter-rate reliability and when employed with a group of adolescent male futsal player, showed that an under-pronated to supinated foot type was associated with higher coach rated ability.<br>-Under-pronated to supinate foot types were |

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| | | | bear weight fully on both feet for measurement of the FPI -6) | | assessed in order to satisfy the data independence requirement for statistical analysis.<br>4) Each item was scored on the 5-point scale, whereby positive score are assigned to pronation, negative score indicative of a supination function. | medial longitudinal arch.<br>6) abduction/adduction of the fore foot.<br>-ability rate (done by the national level coaches)<br>-injury after futsal seasons end (8-month trials) | found to be at significantly higher risk of overused ankle/foot injuries in adolescent futsal player. |
| 12. | (Sabharwal & Singh, 2017) | Foot postural deviations in female kathak dancers | 40 females Kathak dancers<br>-age group 18-35 y/o<br>-minimum dancing experience of 2 years. | To investigate the foot postural deviations among the Kathak dancers. | Subjects were assessed for postural deviation via. Foot postural index, medial longitudinal arch angle, navicular drop, rear foot angle and forefoot angle.<br>The subjects were required to stand still while keeping their lower limbs in relaxed stance position on the floor. | Foot postural deviation, deviation in rear foot angle, deviation in forefoot angle, deviation in medial longitudinal arch angle, deviation in navicular drop and correlation of FPI scores with other postural deviation.<br>(data analyses using Microsoft office excel (mean and standard deviation)) | From the observation, the study concludes that the feet of the kathak dancers are constantly exposed to the forces that can lead to the instability and postural deviations thus the dancers are susceptible to develop many types of foot problems and injuries. |
| 13. | (dos Santos, Gorges, & Rios, 2014) | Individuals with chronic ankle instability (CAI) exhibit | 42 young adults<br>-21 with CAI (13 women and 8 men)<br>-21 healthy | To investigate anticipatory (APA) and compensatory (CPA) postural | 1) Subject was positioned in single-stance with the supporting ankle joint in either one of 2 different positions. | -combination of computer algorithm and visual inspection was used to detect the onsets of leg | Decreased balance sway could be caused by the need for further stabilization of the ankle in more posture recurrent |

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| | | decreased postural sway while kicking in a single-leg stance. | individuals (control group) (13 women and 8 men)<br>Criteria for CAI group:<br>-history of 2 or more sprains of same ankle.<br>-sensations of ankle instability. | adjustments in individuals with and without CAI as they kick a ball while standing in a single-leg stance with their ankle in neutral and supinated position. | 2) The suspended leg was positioned with slight knee flexion and external rotation of the hip; hence the heel of this leg was at the height of the medial malleolus of the supporting leg.<br>3) While standing on the force-plate, the subjects were asked to kick a ball lunched by the experimenter while they were balancing on a single leg.<br>4) The centre of tripod with the ball launcher was placed at a distance of 13.6 cm from the centre of the force-plate surface on which the subjects were positioned.<br>5) The subject is instructed to kick the ball toward the experimenter, aiming through 2 widely-spaced wooden rods positioned in front the ball launcher. | movements and ball impact through the accelerometer signal.<br>-COP displacement during the APA, CPA1 and CAA 2 time intervals were compared using analysis of variance.<br>-COP direction, kicking time (KT), mean velocity (COPap and COP ml) | sprain. |
| 14. | (Konradsen & Voigt, 2002) | Inversion injury biomechanics in functional ankle | 10 anatomical lower extremity specimens were tested. | To test pathogenetic models from the "unprovoked" ankle inversion | 1) Heel-strike test:<br>-specimens were placed in pre-loaded combinations of tibial angulation, internal tibial rotation, plantar flexion | Tibial rotation/tibio talar plantar flexion/subtalar inversion/eversion.<br>-heel-strike | The foot/ankle complex exhibits a high degree of intrinsic stability at heel strike.<br>The foot stabilize will |

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| | | instability: a cadaver study of stimulated gait | | injuries seen in functional ankle unstable subjects. To quantify the degree of passive spatial mal-alignment that would result in an inversion torque during subsequent limb loading in these two situations. | and inversion and transition from unloaded to fully loaded condition was mentioned.<br>-test was made with 10° increments.<br>Swing-phase test:<br>-when subjected to an anterior force, the wagon could run horizontally along the rails causing a collision between cadaver foot and foot plate. | compression<br>-swing phase collison | thus stabilize itself and move into normal eversion at the beginning of the stance-phase.<br>The swing-phase collision model provides a link that can connect the small deficits in inversion angle awareness in chronic functional ankle unstable subjects. |
| 15. | (Rome & Brown, 2004) | Randomized clinical trial into the impact of rigid foot orthosis on balance parameters in excessively pronated feet | 30 female and 20 male healthy subjects with excessive pronated feet.<br>(has foot posture index score more than +5)<br>-randomly assigned to one of 2 group | To evaluate the effect of rigid foot orthosis on balance parameters in subjects with clinically diagnosed excessively pronated feet. | Each subject was instructed to stand with their arms by their sides and looking straight ahead.<br>-intervention group were prescribed foot orthosis.<br>-subjects had 2 anatomical markers placed on the both feet:<br>a)5th metatarsal and insertion site of the Achilles tendon<br>-subjects were then instructed to stand on foot plates and the examiner positioned the subjects' feet.<br>-3 repetitions for each condition were completed. | Analysis using SPSS<br>-standing balance in the form of mean balance (measures the subjects ability to stand with an even load)<br>-Medial-lateral sway and anterior-posterior sway. | The use of foot orthosis in the current study may have improved postural control by stabilizing the rear foot and thus maintaining balance.<br>The benefits of limiting excessive foot pronation may contribute to effective control of internal rotation of tibia. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 16. | (Willems et al., 2005) | Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors) | 223 subjects<br>-3D kinematic, plantar pressure and lower leg alignment data were collected. | To determine gait related risk factors for inversion sprains in a physically active populations | 1) Retro-reflective markers were placed on the thigh, lower leg and rear foot.<br>2) The anatomical markers were placed on the greater trochanter, the medial and lateral femoral condyles, the medial and lateral malleolus, and the medial and lateral part of the calcaneus and on the head of the 1st and 5th metatarsals.<br>3) Standing calibration trials.<br>4) The subjects were asked to run barefoot at a speed<br>5)3 valid left and 3 valid right stance phase was measured. | 1)8 anatomical pressure areas were identifies, based on the peak pressure footprint.<br>2) Mean and standard deviation for peak pressure, absolute impulse and relative impulse. | The finding of this study suggests that effective prevention and rehabilitation of inversion sprains should include attention to gait patterns and adjustments of foot biomechanics. |
| 17. | (Wright, Neptune, Van Den Bogert, & Nigg, 2000) | The effects of ankle compliance and flexibility on ankle sprains | 10 subjects | To examine the influence of changes in subtalar joint flexibility and compliance on ankle sprain occurrence. | 1) Forward dynamic stimulation<br>2) Ankle sprain stimulation -muscles model driven stimulation of 10 subjects performing the landing phase of a side-shuffle movement was performed. | Range of threshold values were used and the number of stimulation that resulted in maximum torque or displacement f=greater than these threshold values were determined<br>Mean peak supination angle and torque and displacement about the subtalar joint examined | The result suggest that increased mechanical laxity does not directly caused an increased in sprain occurrence during side-shuffle movements. |

| | | | | | | | |
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| 18. | (Krähenbühl et al., 2017) | The subtalar joint: a complex mechanism) | - | To give a general overview of the anatomy, biomechanics and radiographic assessment of the subtalar joint. | Subtalar joint movement:<br>Inversion : 25° to 30 °<br>Eversion : 5° to 10 °<br>1) Radiographic evaluation of the hind foot.<br>a) Hind foot alignment assessment using a plain radiographic image.<br>b) Hind foot alignment assessment using CT scan.<br>2) Impact of the subtalar joint on ankle joint osteoarthritis.<br>A) Ankle joint osteoarthritis.<br>b) Compensatory mechanism. | - | Instability and variations of the subtalar joint morphology contribute to failures in the treatment of ankle joint instability and favour the development of ankle joint osteo-arthritis |

From Table 2.1 above, there were more than thirty journals related to this study and eighty of the journal had been summarized into the table above. From these studies, some of the study focus on observing the outcome of the treatment on the subject tested. For example, the used of wedged foot orthosis, applied the lateral wedge on joint moment, effect of medially posted insole during walking and running , impact of rigid foot orthosis and usage of kinesiotaping. The methods and appliance that being used to observed the outcomes of the study were treadmill, Myodat$^{TM}$ 5.0 software and also 3D motion analysis system. While, other studies are focusing on determine the posture and characteristic of the foot. The methods used were foot pressure and CPEI data, foot postural deviation and one of the test that being applied in this study was foot posture index test (FPI).

# CHAPTER 3: METHODOLOGY

## 3.1 Introduction

Chapter three will provide details of the methodology for this study starting from subject's selection, methodology and instrument used for the experiment, process of data collection and how the analysis of the data were done. By following the engineering design process as shown in Figure 3.1, the problem statements for this study stated. Then, we will generate random ideas as in to solve the problem and selecting the best solution for the problem and build the item with the resources that we have. For this study, we want to investigate the biomechanics of unstable subtalar joint in individual with over-pronation and over-supination, thus the most suitable method is by using the Vicon motion analysis system. Then, following with next step which is evaluating either the method used is the suitable test .Last step is the result from the experiment is obtained and analyzed.

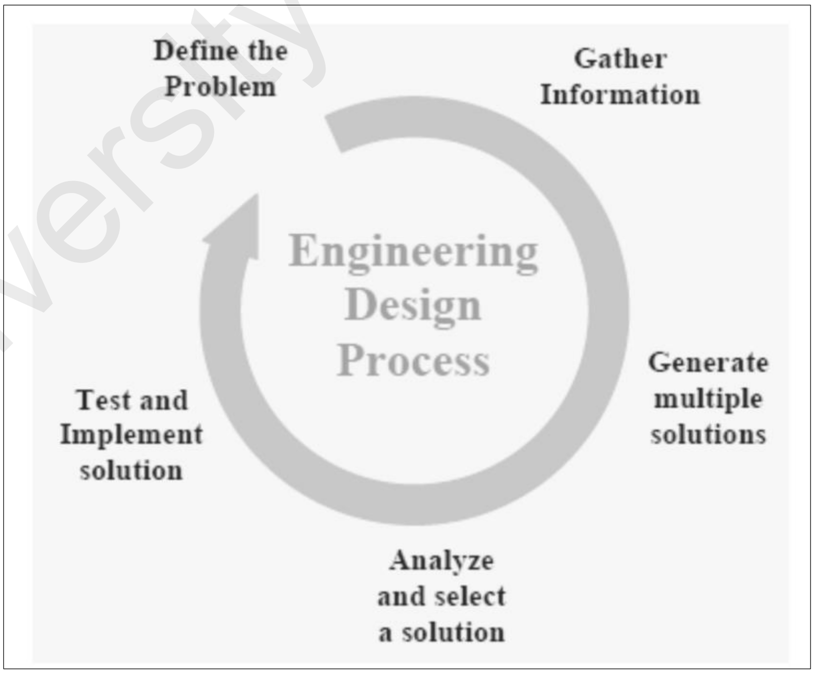


Figure 3.1: Engineering design process. Retrieved from: (Plan & Khandani, 2005)

## 3.2 Subjects selection

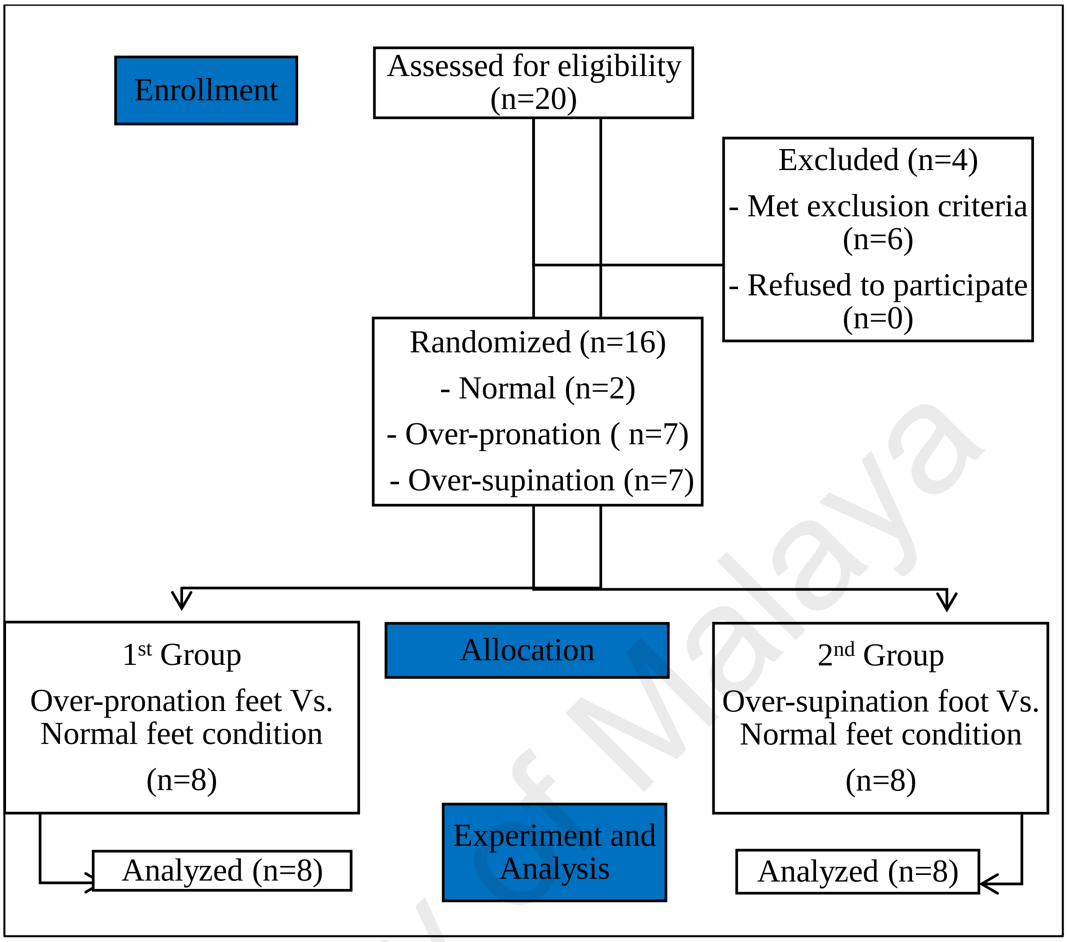


Figure 3.2: Study Design

16 subjects volunteer to participate in this study as shown in study design above Figure 3.2. But after the pre-screening process for inclusion and exclusion criteria as shown in Table 3.1, 16 subjects were recruited to do the test (7 men and 9 female; average age: 24.07±2.6 years; average height 164.37±10.10 cm; average weight 69.64±15.59 kg). Each subject was informed on the objectives of the research and methods of experiment conduction. Their written consent was then obtained as shown in Appendix A. After that, all the subjects were divided into 3 group which are normal (n=2), over-supination (n=7) and over-pronation (n=7).

The inclusion and exclusion criteria for subject selection for this study are simplified as Table 3.1 below. Only subject those following the selected criteria are recruited to continue the test.

Table 3.1: Inclusion and exclusion criteria for subject selection

| Inclusion criteria | Exclusion criteria |
|---|---|
| • The foot posture index (FPI) must be negative score for over-supination foot and positive score for over-pronation. | • Has normal foot posture index |
| • No lower limb injuries. | • Has a history of lower limb injuries. |
| • No history of concussions or visual or vestibular disorders. | • Has a history of concussions or visual or vestibular disorder. |
| • Presents a positive rear foot angle (over-pronation) obtained by subtracting the leg angle from the calcaneal angle while standing.<br>• Presents a negative rear foot angle (over-supination) obtained by subtracting the leg angle from the calcaneal angle while standing.<br>• Presents a rear foot angle of 0 degrees (normal) during standing. | • Presents any other musculoskeletal foot disorders except for over-pronation and over-supination. |
| • Presents an LAA $\leq 134^0$ (over-pronation) or $\geq 152^0$ (over-supination) while weight bearing. | • - |

## 3.3 Ethical Approval

This research was conducted with the approved permission by the National Medical Research Register Secretariat 37912 and under the guidance of Certified Prosthetist and Orthotist (CPO) of the International Society of Prosthetics and Orthotics (ISPO) Category-2. All subjects were required to sign a written consent form prior to the tests.

## 3.4 Experimental procedure

All experiments were performed in the video-based motion analysis laboratory. All the kinematic parameters were recorded and captured using five infrared camera and 16 passive reflective sphere markers that were attached to the subjects' lower limb. The kinetic data was determined using two rectangular metal force plates embedded in the floor of the walkway. The Vicon$^{TM}$ Nexus 1.3 software enables the connection to the infrared camera and was used to complete the calibration procedure and analysis of data. The experimental set-up for this study is show in Figure 3.3 below.

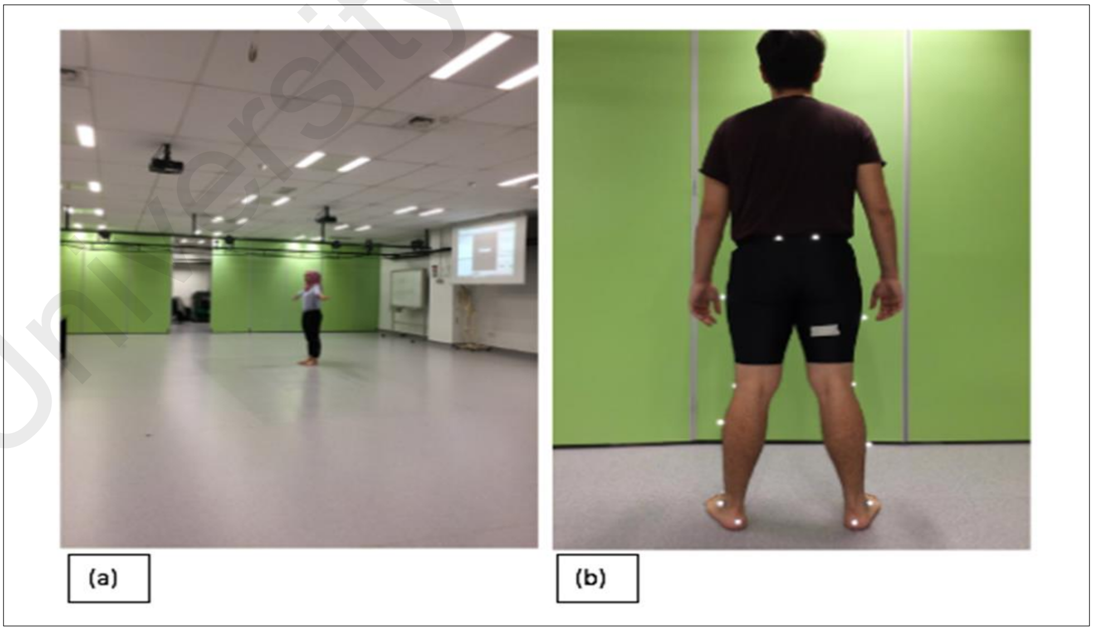


Figure 3.3: The experimental set-up (Vicon Motion Analysis); (a) the position of the subject during the T-pose procedure and (b) the 16 passive markers positions on the lower limb of the subject.

*System setup*

First step of this experiment was the calibration of the system. The calibration system was done to define the loco (joint) and lab (global) coordinate system so precise data can be obtained. By moving the wand around the space of experiment or region field of camera we can calibrate the system and connect the infra-red camera and the Kisler force plate system. The sampling frequency used for this study was 100 frames per second.

*Subject Preparation*

Make sure that the subject was wearing proper cloth for the experiment which was tight fitted cloth so the marker placement was fixed on its position and visible to all the cameras during the experiment.

Then, the following measurements were taken to be inserting into the Vicon™ Nexus 1.3 software before the experiment. The measurements were weight (kg), height (Karlsson et al.), right and left leg length (Karlsson et al.), right and left knee width (Karlsson et al.) and right and left ankle width (Karlsson et al.). Lastly, 16 passive reflective marker position on the body segment as in Table 3.2 below and name of the position as table below:

Table 3.2: 16 passive reflective markers position

| No. | Right side | Left side |
|---|---|---|
| 1. | Right 2nd metatarsal joint | Left 2nd metatarsal joint |
| 2. | Right heel | Left heel |
| 3. | Right lateral malleoli | Left lateral malleoli |
| 4. | Right tibia | Left tibia |
| 5. | Right lateral knee condyle | Left lateral knee condyle |
| 6. | Right mid-thigh | Left mid-thigh |
| 7. | Right anterior superior iliac spine (ASIS) | Left anterior superior iliac spine (ASIS) |
| 8. | Right posterior superior iliac spine (PSIS) | Left posterior superior iliac spine (PSIS) |

*Experiment procedure*

Firstly, the Vicon$^{TM}$ Nexus 1.3 software was opened and a new subject and session was created. Then, all the measurement data was entered into the system under the plug-in gait section. After that, the subject was asked to stand in a T-pose position and the video was recorded. Static plug-in gait analysis was done using the video captured and all the markers were labeled in the system according to The Helen Hayes market set placement.

Each subject was asked to walk on the walkway that had been embedded with two-force plates on the floor, every time a new trial was done make sure that force-plates were zero-level. Dynamic plug-in gait test which were the self-selected walking speed was done. Each subject was informed of the experiment procedure and given time to practice walking ensuring each foot is placed on each force plate alternatively.

The subjects were walking in barefoot condition in order to observe their way of walking without controlling by others factor such as shoes design and height of the insole. After subject was ready he/she was asked to begin walking and then the start button was pressed. Each test will be repeated five times in order to get the average and the analyses were done by findings the means values for each parameter. The experimental data was then processed and saved.

*Formula for Joint Angle, Moment, Power and Ground Reaction Forces*

Joint Angle was calculated based on Figure 3.4 below where V may be assigned as subject ankle joint. The anatomical-based angles should be 90 degrees but for the ankle the anatomical based angle should be consider as 0 degrees as shown below. The movement of the ankle in the dorsiflexion will increase the angle (positive degree) and plantar flexion angle will degree the angle (negative degree). The coordinate system for the ankle joint used for this study was as shown below.

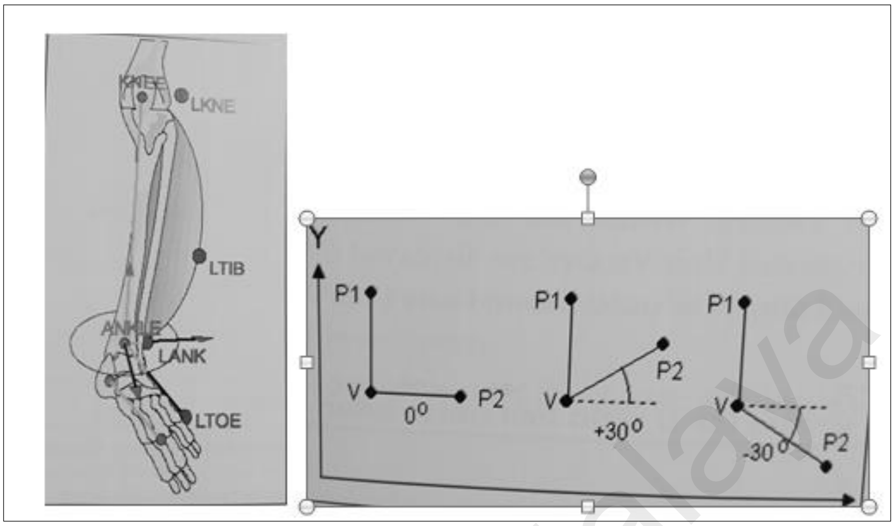


Figure 3.4: The ankle embedded coordinate system and point V may be assigned as the subject ankle joint. Retrieved from: (Abu Osman & Mohd Ismail, 2009)

The joint moment, $M_j$ (N*m/Kg) was the moment that generated by the force at the center of gravity (McGowan, Baudinette, & Biewener, 2005).

$\sum F_{x,y} = ma_{x,y}$ ………………………..(1)

$\sum M_j = I_j a_j$……………………………..(2)

$F_{x,y} = The\ external\ force\ in\ the\ horizontal\ and\ vertical\ direction$

$m = mass\ of\ the\ segment$

$a_{x,y} = The\ linear\ acceleration\ of\ the\ center\ of\ gravity\ in\ both\ direction$

$I_j = moment\ of\ inertia\ about\ the\ center\ of\ gravity$

$a_j = angular\ acceleration$

The Joint power (W/Kg) was calculated as below, when M and $\omega$ are in the same direction at the particular joint, the joint power produce is in positive quantity since the energy is generated due to concentric action in the muscle across the joint. While if the M and $\omega$ are in opposite direction, the power will be negative due to the energy is absorbed to eccentric the muscle action.

$P = M\omega$……………………………(3)

$M = \ moment\ of\ the\ force$

$\omega = the\ direction\ of\ joint\ moment$

The Ground Reaction Force (GRF) was calculated as equation below:

$L/RGroundReactionForce\ = \ X/m$

$NormalizedGRF = X/(m * g) * 100\%$

$g = gravity$

$m = patient's\ mass$

$x = reading\ from\ force\ plate$

## 3.5 Data Analysis

The observation was done based on 4 importance phases involving the ankle movement in the gait cycle. Phase 1 is the initial contact (heel strike). Phase 2 is the foot flat position where the ankle then undergoes dorsiflexion. Phase 3 is the heel beginnings to lift at the beginning of the double support followed by phase 4 which is the swing phase.

All of the data analysis was done using the Vicon™ Nexus 1.3 system, the file was import to the system. From raw marker data that we obtained during experiment, the core processing in the software will automatically reconstruct, label and kinematic fitting to produce 3D trajectories. Then, the subject calibration was done to label the skeleton; the time bar can allow us to select our desire frame. The system automatically helps to fill gaps and the data was filter using low-pass Butterworth to reduce the noise produce during data collection.

Lastly, the data processing was done by the software to produce model outputs with force, moments, joint angles and other data. Then, the data was plot and analyses using the MATLAB_R2019a software and one-way ANOVA were done to compare the data between normal and over supination condition. The statistical significance level was p-value =0.05 based on the literature review done on previous study.

# CHAPTER 4: RESULTS AND DISCUSSION

This chapter gives an overview about information of the data collected from the experiment. The results are divided into two different sections which are over-supination feet and over-supination feet condition.

## 4.1 Introduction

All the subjects demographic characteristics data were simplified and tabulated as in Table **4.1** below.

Table 4.1: Subjects demographic characteristics.

| | Normal group | | Over-supination foot group | | Over-pronation foot group | |
|---|---|---|---|---|---|---|
| | Mean (±SD) | Range | Mean (±SD) | Range | Mean (±SD) | Range |
| N | 2 | - | 7 | - | 7 | - |
| Age(year) | 26.5±0.71 | 26.0-27.0 | 23.14±1.35 | 22-25 | 24.4±2.51 | 22-28 |
| Weight(kg) | 62.5±6.36 | 58.0-67.0 | 70 ± 16.73 | 51.5-91 | 72.0±18.10 | 55.5±102.5 |
| Height(cm) | 159.85±2.33 | 158.2-161.5 | 167.36±12.52 | 156-185 | 162±7.87 | 151-169 |
| Body mass Index (kg/$\mathbf{m^2}$) | 24.5±3.25 | 22.2±26.8 | 24.67±3.07 | 21.2-27.6 | 27.26±5.76 | 22.3-35.7 |
| Foot Posture Index (FPI) | -0.5 ±0.71 | 0 to -1 | -10.14 ±1.35 | -8 to -12 | 7.8±0.84 | 7-9 |
| Walking Distance (km) | 8.50±0.71 | 8-9 | 8.71±0.76 | 8-10 | 8.6±0.89 | 8-10 |

*SD= Standard Deviation

There were no significant differences between the groups of normal foot condition and over pronation foot condition for age (p = 0.16), height (p = 0.75), body mass (p = 0.45) or BMI (p = 0.46).

Ankle angle (degrees), power (W/kg), moments (N.m/kg) and GRF (N/kg) of each foot functions were processed using the Vicon$^{TM}$ Nexus 1.3 software. Joint moment is the product of force with distance of force from the center of joint while joint power is the result of angular velocity multiply the joint moment.The over-pronation feet and over-supinated feet condition were analysed separately with comparison to the normal foot function.

### 4.2 Over-pronation Foot

The result from the motion analysis test for 7 over-pronation subjects and 1 normal subject were translated into the graphs shown in Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4. In this motion analysis test, the main objective was to discovered the forces acting on the ankle joint, the angle of ankle joint, moment of ankle joint and power of ankle joint for the over pronation foot during gait cycle. All the data collected were analyzed using the Vicon™ Nexus 1.3 system, the results from the over pronation foot were compared to the normal foot in order to observe the different and the gait pattern.

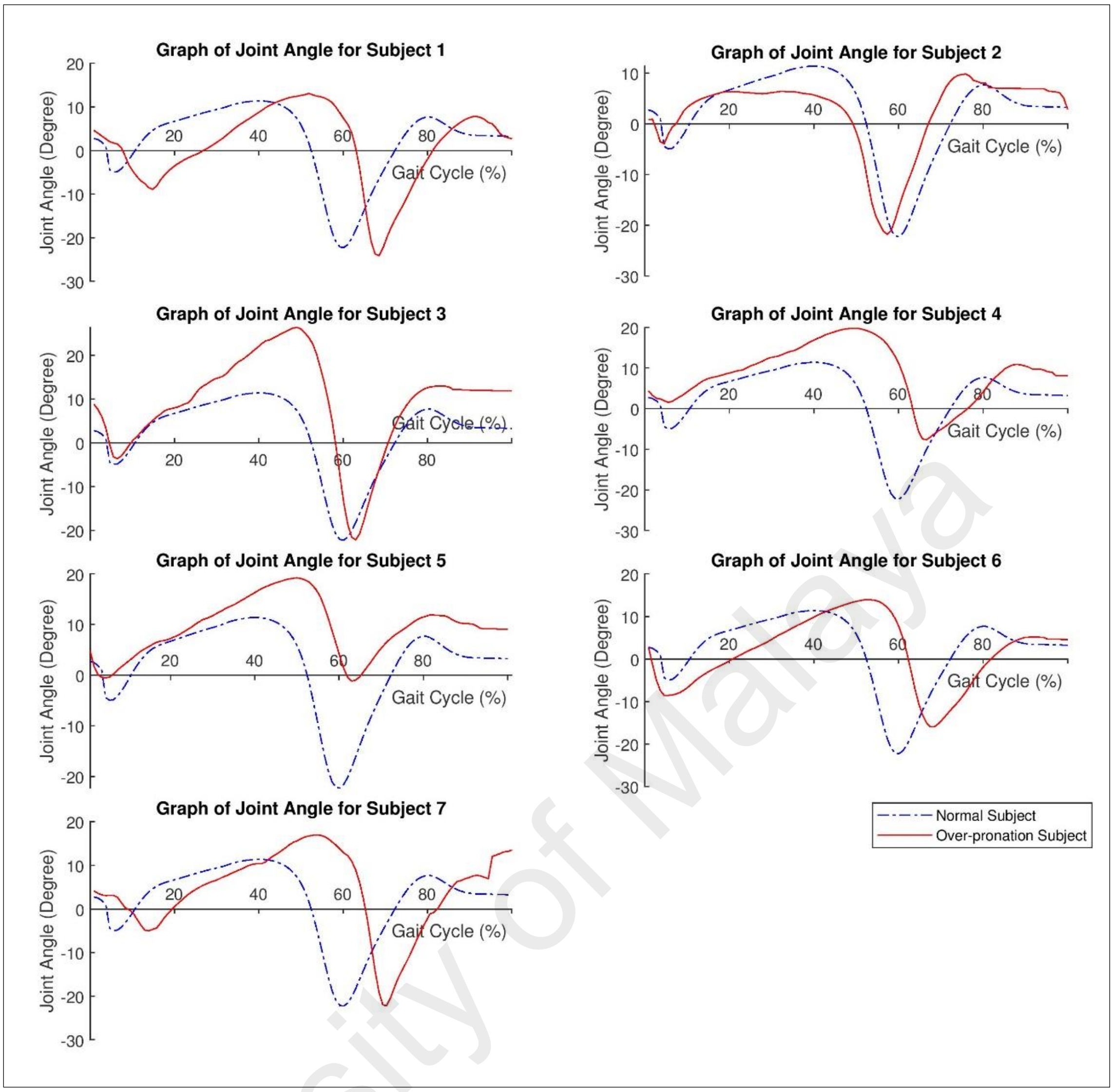


Figure 4.1: Graph of Ankle Angle for a complete gait cycle (100%) for each subjects (Dash dot blue line represent the Normal subject and red line represent Over-pronation subject)

There were 4 importance phases through the ankle joint in the gait cycle. Phase 1 was the initial contact, phase 2 was the position of the foot flat the ankle then begins to dorsiflexion; phase 3 was the heel begins to lift at the beginning of the double support and phase 4 was during the swing phase. All these 4 phases can be observed on the Figure 4.1 above.

From Table 4.2 below, the result obtained for ankle angle was for the over-pronation subjects compared to a subject with normal foot condition in sagittal plane. For the phase 1 that was at the initial contact or heel strike subject 1- subject 7 show the joint angle of 4.6°, 0.92°, 8.76°, 4.35°,4.86°, 2.72°and 4.13° respectively. For normal people, the phase 1 angle of ankle joint was around 3-5 degree dorsiflexion. Thus, subject 1, 4, 5 and subject 7 were in the range of normal ROM during phase 1, subject 2 and subject 6 shown less dorsiflexion movement compare to normal feet condition which is happed due to over-pronation feet condition. Moving to the loading response phase, the foot gradually becomes plantar flexion before ready to dorsiflex the foot to mid-stance phase. The entire ankles for over-pronation subjects were doing plantar flexion movement. Subject 2 and 6 excessively plantar flex their ankle which were -8.90° and -8.56° respectively.

For phase 2 where the position of the foot flat the ankle then begins to dorsiflexion, the foot remain stationary and tibia become the moving segments. The maximum angle of ankle joint during this phase for subject 1 until subject 7 were 11.52°, 6.34°, 16.87°, 12.91°, 12.43°, 7.90° and 9.72°. The maximum ROM of ankle joint for normal person during this phase was 10-degree dorsiflexion thus subject 2, 6 and 7 shows dorsiflexion angle less than normal subject.

For phase 3, the heel begins to lift at the beginning of double support that will cause the ankle plantar flexion. The maximum angle of ankle joint during this phase for subject 1 until subject 7 were -22.24°, -24.14°, -21.82°, -22.18°, -7.64°, -1.16°, -15.95° and -22.12°. The normal ROM during this phase was 20-degree plantar flexion, all subjects' shows that the foot does plantar flexion during this phase but subject 5, 6 and 7 show less plantar flexion angle compare to normal feet condition. In phase 4, the foot was in swing phase, thus the ankle rapidly dorsiflexion to allow the clearance of the foot from the ground. The ankle angle during this phase for subject 1 until subject 7 were 7.69°, 9.82°, 8.58°, 12.91°, 10.75°, 11.88°, 5.11° and 7.71°. During this phase, the foot was ready to back into phase 1 again, thus the degree of ankle during this phase for normal people was 3-5 degrees. All subjects were exceeding the normal ROM during this phase 4.

From the statistical analysis done for each subject to find the difference of ankle joint angle between normal feet condition with over-pronation condition to prove the null hypotheses which both normal and over-pronation condition have same range of angle. From the analysis, the p-values for subjects 2, 3, 5, 6 and 7 were less than α value which is 0.05. This indicates that there is a significant difference of angle between normal feet condition with over-pronation condition thus the null hypothesis is rejected. In addition, there were two other subjects which were subject 1 and subject 4 shows p-values more than 0.05 and accept the null hypotheses. Even though the subjects were present with over-pronation condition but the joint angle does not shows many difference compare to normal foot condition.

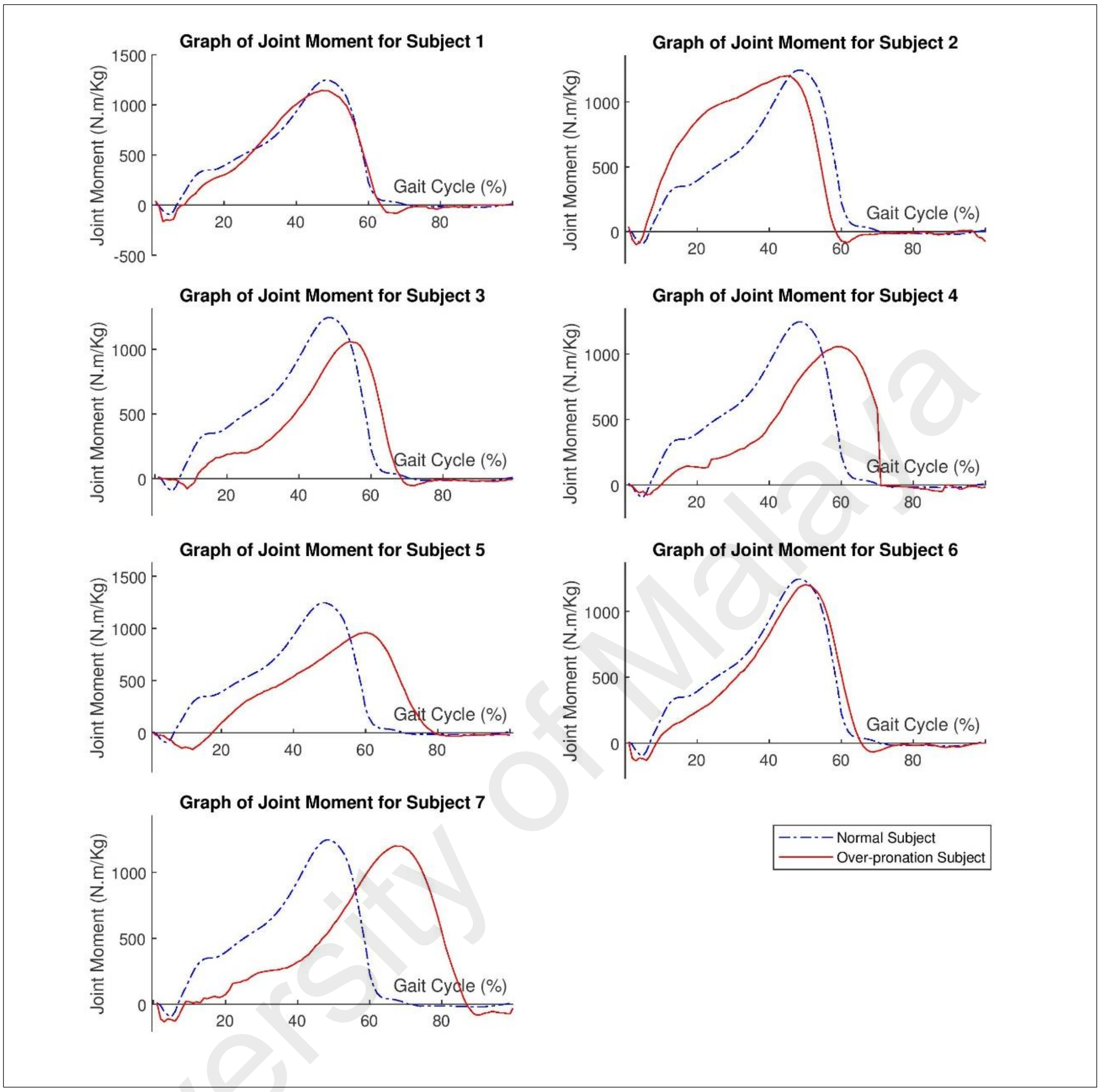


Figure 4.2: Graph of Ankle Joint Moment for a complete Gait cycle (100%) *A1 is the negative region of the y-axis and A2 is the positive region of y-axis (Dash dot blue line represent Normal subject and red line represent Over-pronation subject)

The muscles will produce moment of force across during walking. The moment can be analyzed using the gait cycle analysis in the motion analysis laboratory. The total moment at the joint was the product of two measurable quantities that were the joint segment's moment of inertia, in this cases the ankle masses and length of foot and the joint's angular acceleration during gait cycle. From Figure 4.2, the peak joint moments can be observe at both graphs. Each subject have their own peak joint moment, it depend on the maximal torque and twisting loading on the joint and joint angular impulse that happened during stance phase. It was determine by multiplying the load by the length of time it was applied on the ankle joint.

From Figure 4.2, the peak joint moment for left ankle joint in subject 1 was 1.14k Nm/Kg, for subject 2 was 1.20k Nm/Kg, for subject 3 was 1.6 Nm/Kg, for subject 4 was 1.06kNm/Kg , subject 5 was 0.96k Nm/Kg, subject 6 was 1.20k Nm/Kg and subject 7 was 1.20k Nm/Kg. From the statistical analysis for joint moment between these two group, the p-values for all subjects were less than 0.05 thus reject the null hypotheses and indicates that there were significant different between over-pronation foot with normal feet condition in terms of joint moment.

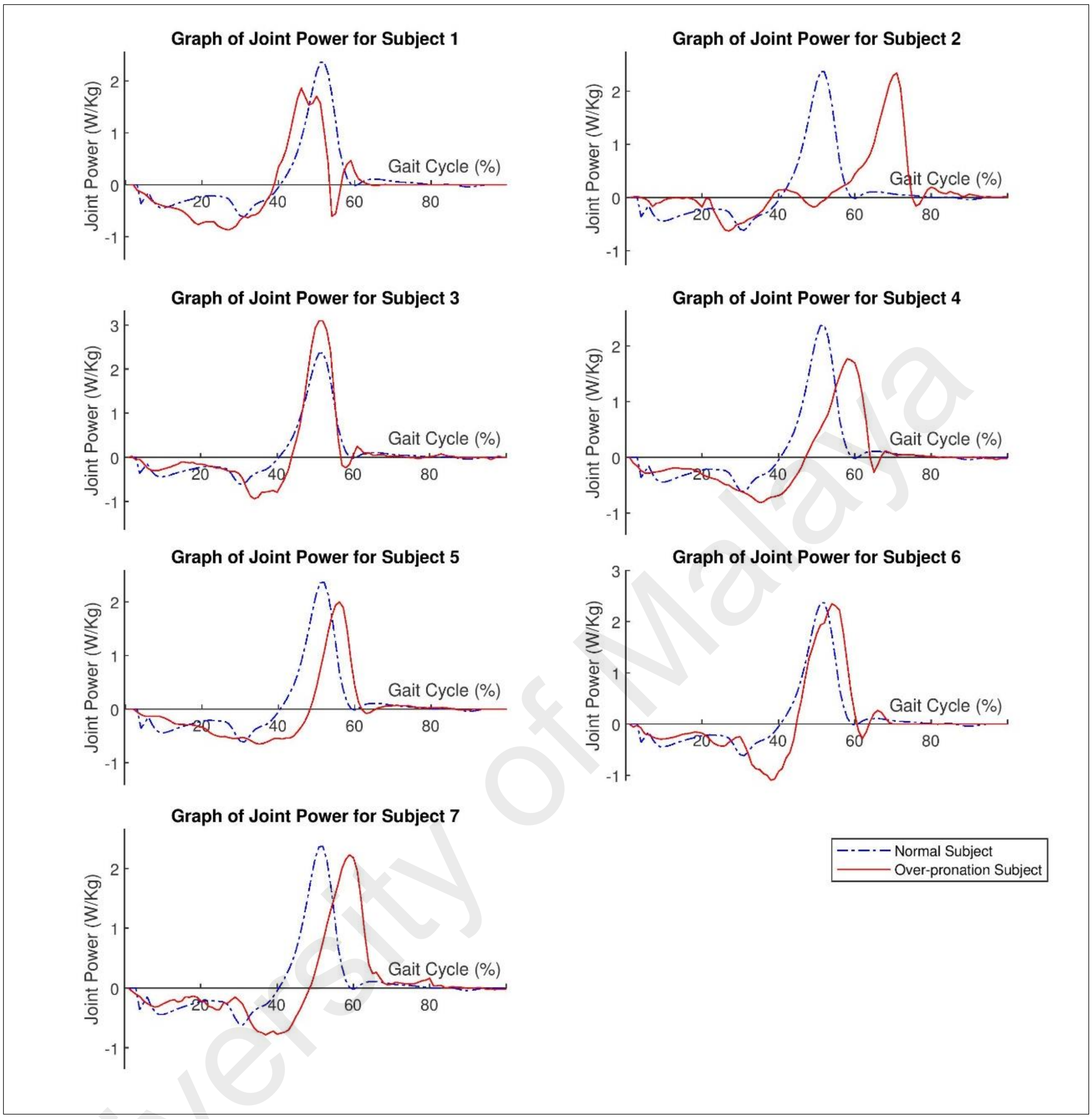


Figure 4.3: Graph of Ankle Joint Power for a complete Gait cycle (100%) for each subject (Dash dot blue line represent Normal subject and red line represent Over-pronation subject)

From Figure 4.3 above, the graph were represent the power that acting on the ankle joint for left and right of the foot. There were two regions that were A1 and A2 region. A1 region was representing the region for the negative power. The negative power at the A1 region was corresponding to the eccentric plantar flexor activity at the ankle during mid-stance and terminal stance.

While A2 region was the positive power that was corresponding to the concentric burst of propulsive plantar flexor activity during pre-swing. Since all subjects had different muscle structure and different body mass, it shown in the graphs that each subject will had different power for muscle eccentric and concentric during the gait cycle. From Figure 4.3, the peak positive power that happen on the A2 region for left ankle joint for subjects 1 was 1.87W/Kg, for subject 2 was 2.34 W/Kg, for subject 3 was 3.09 W/Kg, for subject 4 was 1.74 W/Kg, subject 5 was 2.00 W/Kg, subject 6 was 2.35 W/Kg and subject 7 was 2.22W/Kg.

While for the peak negative power that was at A1 region for left ankle joint for subject 1 was 0.48W/Kg, for subject 2 was 0.61W/Kg, for subject 3 was 0.30 W/Kg, for subject 4 was 0.27 W/Kg, subject 5 was 0.30 W/Kg, subject 6 was 0.29 W/Kg and subject 7 was 0.32 W/Kg. From the statistical analysis for joint power between these two group, the p-values for all subjects were less than 0.05 thus reject the null hypotheses and indicates that there were significant different between over-pronation foot with normal foot condition in terms of joint power.

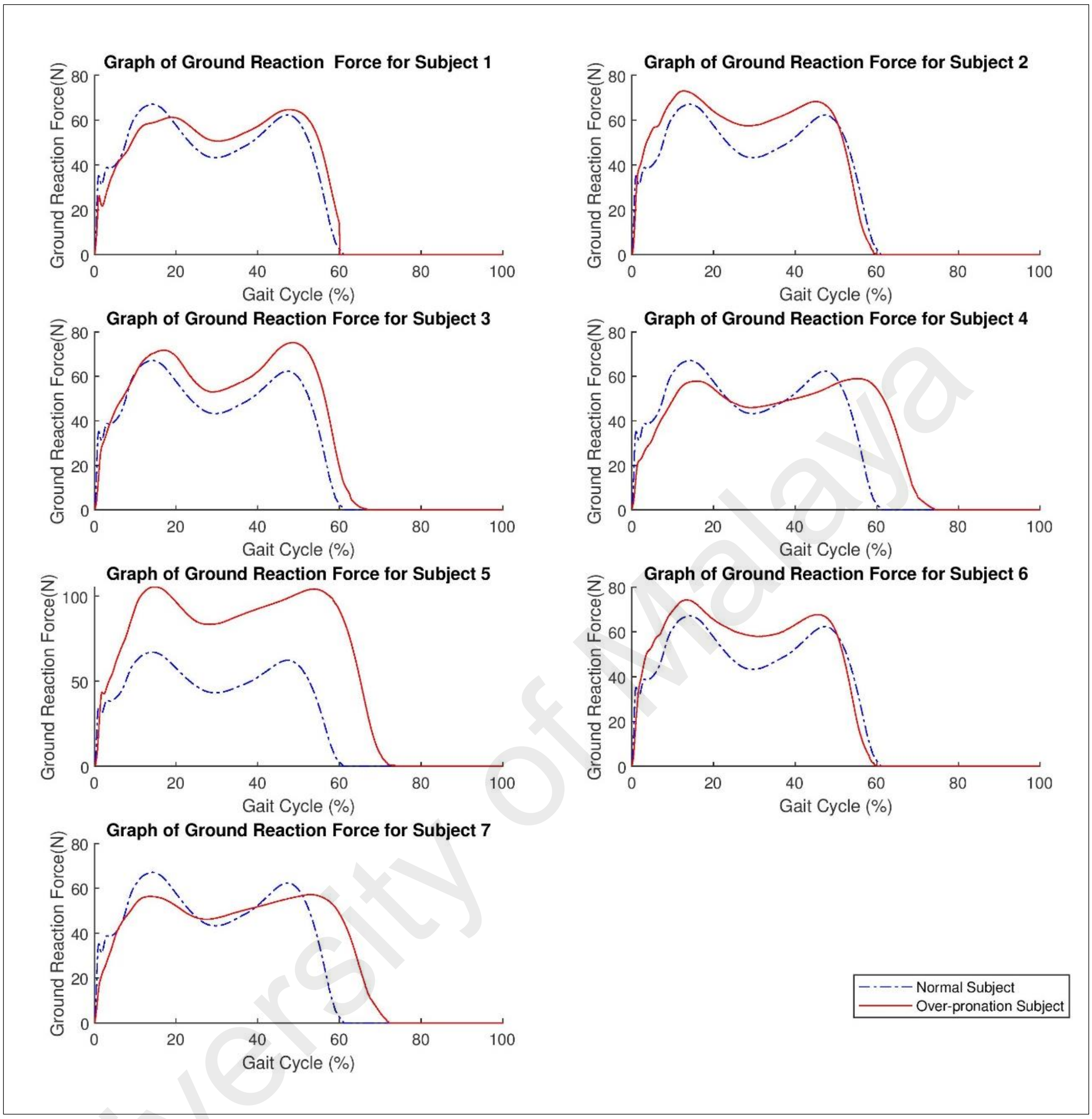


Figure 4.4: Graph of GRF for each subjects in a complete Gait cycle (100%) (Dash dot blue line represents Normal subject and red line represent Over-pronation subject)



Figure 4.4 above show the ground reaction force that acting on the force plate 1 during the gait cycle. All 7 subjects were doing gait cycle analysis, a complete gait cycle that acting on both force plate were translated into the graphs above. From Figure 4.4, the observation that can be made was the maximum vertical force; $Fz$ acting on subject 1 was 61.19 N and drop to 50.68N. For subject 2, the maximum $Fz$ was 72.96 N and drop to 57.56 N and for subject 3 maximum $Fz$ was 71.62 N and drop to 53.23 N. Subject 4 show the maximum $Fz$ of 57.74 N and drop to 46.01 N. Subject 5 show the maximum $Fz$ of 105.39 N and drop to 83.50 N. Subject 6 show the maximum $Fz$ of 74.24 N and drop to 58.05 N. Subject 7 show the maximum $Fz$ of 56.20 N and drop to 46.29 N. From the statistical analysis for ground reaction force between these two group, the p-values for all subjects were less than 0.05 thus reject the null hypotheses and indicates that there were significant different between over-pronation foot with normal foot condition in terms of GRF.

The vertical force was largest component of the GRF and represent on the M graphs and it was the acceleration of body center mass in the vertical direction during gait. The maximum vertical force can reach to 120 % of body weight during double stance and drop to 80 % of body weight during single stance(Ryu & Park, 2018).

One complete gait cycle was consisting of 2 phases that were stance phase and swing phase. The stance phase represents 60% of the gait cycle graph and swing phase represent 40% of the graph. Firstly, the kinetic parameter was the ground reaction forces (GRF) that develop during the gait cycle due to the force applied to the ground when the foot was contact to it. There were three main components of GRF during gait cycle that were vertical force, anterior/posterior force and medial/lateral forces (Kluitenberg, Bredeweg, Zijlstra, Zijlstra, & Buist, 2012).

Vertical force was the largest component on the GRF as it represents the acceleration of the body's mass center in the vertical direction during locomotion. It was resulted from BW and shear forces due to friction between the foot and the ground. Thus, as body weight acting downward, it will generate an equal and opposite upward ground reaction. Therefore, the graph as in Figure 4.4 shows that the GRF on each subjects were varies according to the subject BW. The higher the BW of the subject, the higher the ground reaction forces that acting on the force plate 1 and force plate 2. The GRF were higher during heel strike as the whole body weight was applied on the heel and then the GRF will drop during the mid-stance because the force was applied on the foot at large area compare to during the heel strike. Lastly, the GRF will increase again during the last phase of the gait cycle that was during toes off. For all 7 subjects, the peak GRF was in the range of 0.59kN-1.05kN depends on the body weight for each subject, it still in the range of normal peak vertical GRF value that was maximum can achieved was 1.2kN. While for the dropping vertical force during the mid-stance phase of the foot was in the range of 0.47kN-0.88kN, the force was drop because it was distributed on the foot area rather that at one point only. Subject 5 had higher dropping vertical GRF that was about 0.88kN compare to normal value 0.80kN, this happened because of the excessive body weight of the subject causes the increase of force on contact to the ground during gait. The Vertical GRF can be reduced by adding an insole because it can add cushion area and reduce the time impact and contact of heel and toes toward the ground during walking (Alam, Garg, Munia, Fazel-Rezai, & Tavakolian, 2017).

Secondly, the kinematic measurement that being observe was the range of motion, ROM of ankle joint during the gait cycle. The ROM was importance because it will determine the movement of the ankle during walking. The movement of the ankle joint was very importance because it allows shock absorption at heel strike; progression of the body forward during the stance phase and most importantly for pushes off before toes leaves the ground during stance phase. While for the swing phase, it functions as the foot clearance from the ground. For the ROM, there were 4 phases that need to be consider, first was phase 1 that was the beginning of the gait cycle or known as initial contact or heel strike. During this time, the ankle joint was in neutral position, then it begin to plantar flex to between 3 – 5 degrees until the foot transfer into the next phase that was foot flat. This phase 1 acting like a first rocker since the foot was pivoting about the heel. At this phase, the dorsiflexors muscles in the anterior compartment of the foot and ankle that was tibialis anteriorly were eccentric to control the plantar flexion of the foot. This will gives the effects of a shock absorber and will help to smooth the weight acceptance to the lower limb (Hajirezaei, Mirzaei, & Khezri, 2017). During this phase only subject 2 and subject 6 shows lower ankle angle that is 0.92° and 2.72° respectively. This may be due to severe flat foot condition than lead to the subject having difficulty to control the foot during heel strike thus lower the ankle angle and jump to the second phase. Other subject also had lower value of ankle angle but they were still in the range of normal ankle angle that was 3 to 5 degrees. This indicates that may be other subject was cope and better training with the flat foot condition and has a better control of their muscle compare to subject 2.

Flat foot condition was associated with over pronation of the foot, subjects will tends to land quickly to the second phase because they need to stabilized the body since the arch cannot helping in muscular support thus subject will lend toward the medial aspect of the foot. During this phase the power acting on the joint was negative because our body was absorbing the energy to elongate the muscle, that why all the subjects ankle joint power was below than 1.0 W/Kg during this phase.

For phase 2, the foot was in flat condition and the ankle begins to dorsiflexion. Tibia play importance role to move while the foot remains stationary, the joint can reached maximum of 10 degree when the tibia move over the ankle joint. At this time the plantar flexor muscle was acting eccentrically to control the movement of the tibia forward. Thus at this phase, the power was still in the negative power phase. At this phase 2, all subjects were exceeding the normal ROM of ankle joint that was 10 degree. This was because the joint need to have bigger rocker system to support the foot in order to move it forward since the arch of the subjects cannot support it due to flat foot condition and the joint was in inward position.

Thus, the muscle cannot help to control the movement of the foot during plantar flexion thus make the ankle angle more than 20 degree. This result was supported by the journal that state the plantar flexion angle for the flat foot was more than 23 degree (Banwell, Paris, Mackintosh, & Williams, 2018). At this phase, the plantar flexor muscle in the posterior compartment that known as gastrocnemius contract concentrically in order to pushing the foot into plantar flexion and propelling the body forward. This was the start of the positive power phase to happen because our body generates energy through the concentric muscle activity (Wang & Brown, 2017).

Last was phase 4, this was the swing phase of the gait cycle and the joint will move in dorsiflexion movement in order to clear the foot from the ground. Then at the end phase 4, the foot was ready to heel strike. During the dorsiflexion movement, the muscle was concentric contract in order to provide foot clearance and ready for next foot strike, the joint angle at this phase was between 3 to 5 degrees. All subjects exceed the normal ROM of joint at this phase; it was because the joint try to stabilize the body and ready to make a strike. As in journal state that it was reasonable for the swing ankle angle to have bigger range in order to have higher walking stability and a lower initial walking speed for the next strike (Zang, Liu, Liu, Iqbal, & Zhao, 2016).

For the patient with over pronation, the excessive eversion of the foot will not only cause extra tibia rotation but also can overloading the stress on the knee and cause knee pain and other deformity. Excessive pronation during gait cycle can also increase the tibia-fascia traction especially during running, it was due to the contraction of superficial and deep ankle plantar-flexors during stance phase in order to counter back the excessive pronator motion of the foot (Bandholm, Boysen, Haugaard, Zebis, & Bencke, 2008).

To investigate the pattern of walking in order to determine the effect of over pronation foot to the gait cycle, gait analysis was done. Thus, this motion analysis on the subjects with over pronation foot can help to identify the movement of the foot frame by frame observation of motion and kinematic also kinetic such as the ankle angle, moment, power and force acting on the joint during one complete gait cycle. This enable physician to further investigate into the joint motion and assist in determines the orthotic recommendation or modification to the patient with over pronation foot for the proper treatments.

Therefore a suitable arch support or insole that can support the medial side of the foot can be prescribed to the subjects, but the thickness of the insole was depending on the condition of the subject. This medial support insole can helping in stabilizing the joint during the initial phase thus can reduce the force acting on the joint (Kosonen et al., 2017).

Table 4.2: Summary of ankle kinetic and kinematic parameter data for a complete gait cycle for over-pronation feet condition

| Parameters | | Ref | N1 | OP1 | OP2 | OP3 | OP4 | OP5 | OP6 | OP7 |
|---|---|---|---|---|---|---|---|---|---|---|
| Angle ((IPH)) PF (–ve)/DF (+ve) | IC | 0 | 2.97 | 4.60 | 0.92 | 8.76 | 4.35 | 4.86 | 2.72 | 4.13 |
| | LR | -5 | -4.93 | -8.90 | -3.52 | -3.62 | 1.55 | -0.44 | -8.56 | -4.85 |
| | MSt | 10 | 9.54 | 11.52 | 6.34 | 16.87 | 12.91 | 12.43 | 7.90 | 9.72 |
| | TSt | 10 | 9.86 | 12.06 | 5.52 | 25.99 | 19.42 | 19.09 | 13.45 | 16.09 |
| | PSw | -20 | -22.24 | -22.14 | -21.82 | -22.18 | -7.64 | -1.16 | -15.95 | -22.12 |
| | ISw | -10 | -20.16 | -18.81 | -18.17 | -20.88 | -6.17 | -0.39 | --14.29 | -20.25 |
| | MSw | 5 | 7.69 | 9.82 | 8.58 | 12.91 | 10.75 | 11.88 | 5.11 | 7.71 |
| | TSw | 0 | 2.99 | 2.97 | 2.91 | 11.85 | 8.14 | 9.07 | 4.54 | 13.19 |
| Moment (kN.m/kg) PF (+ve)/DF (-ve) | -ve region | -0.30 | -0.57 | -1.50 | -1.00 | -0.80 | -0.49 | -1.25 | -1.11 | -1.11 |
| | +ve region | 1.57 | 1.25 | 1.14 | 1.20 | 1.06 | 1.06 | 0.96 | 1.20 | 1.20 |
| Power (W/kg) | A1 region | -0.5 | -0.41 | -0.48 | -0.61 | -0.30 | -0.27 | -0.30 | -0.29 | -0.32 |
| | A2 region | 3.5 | 2.37 | 1.86 | 2.34 | 3.09 | 1.74 | 2.00 | 2.35 | 2.22 |
| GRF (N) | HS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Spike | 80 | 34.77 | 25.37 | 33.38 | 31.81 | 21.86 | 42.60 | 34.25 | 19.49 |
| | FP | 120 | 66.85 | 61.19 | 72.96 | 71.62 | 57.74 | 105.39 | 74.24 | 56.20 |
| | MSt | 59 | 43.27 | 50.68 | 57.56 | 53.23 | 46.01 | 83.50 | 58.05 | 46.29 |
| | SP | 110 | 62.63 | 64.49 | 68.23 | 75.10 | 59.00 | 103.28 | 67.61 | 57.02 |
| | Toe off | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*FP: First peak; SP: Second peak; OP: Over-pronation; N: Normal; Ref: Reference
PF: Plantarflexion; DF: Dorsiflexion (IC: Initial contact; LR: Loading response; MSt: Mid stance; TSt: Terminal stance
PSw: Pre swing; ISw: Initial Swing; MSw: Mid Swing; TSw: Terminal swig

## 4.3 Over-supination Feet

The results for over-supination foot group were illustrated as in Figure 4.5- Figure 4.8 below. Each graph represents the joint angle, joint moment and joint power of all subjects that focus on the ankle joint in sagittal plane because at this plane larger movement occurs. In the figures, there were 7 subplot graphs where each graph represents the movement of 7 over-supination foot subjects. Through these figures, we can compare the pattern for over-supination and normal condition. The measurement of the movement such as angle, moment and joint power are the kinematic parameters that being analyzed in this study. The angle was measure in the unit of degree (Figure 4.5), joint moment in newton-meters per kilogram body mass (Figure 4.6) and joint power in unit of watts per kilogram body mass as Figure 4.7. While for kinetic parameter was the measurement of the force involved in producing these movement that was the vertical GFR in unit Newton(N) that acting on the body during walking as shown in Figure 4.8.

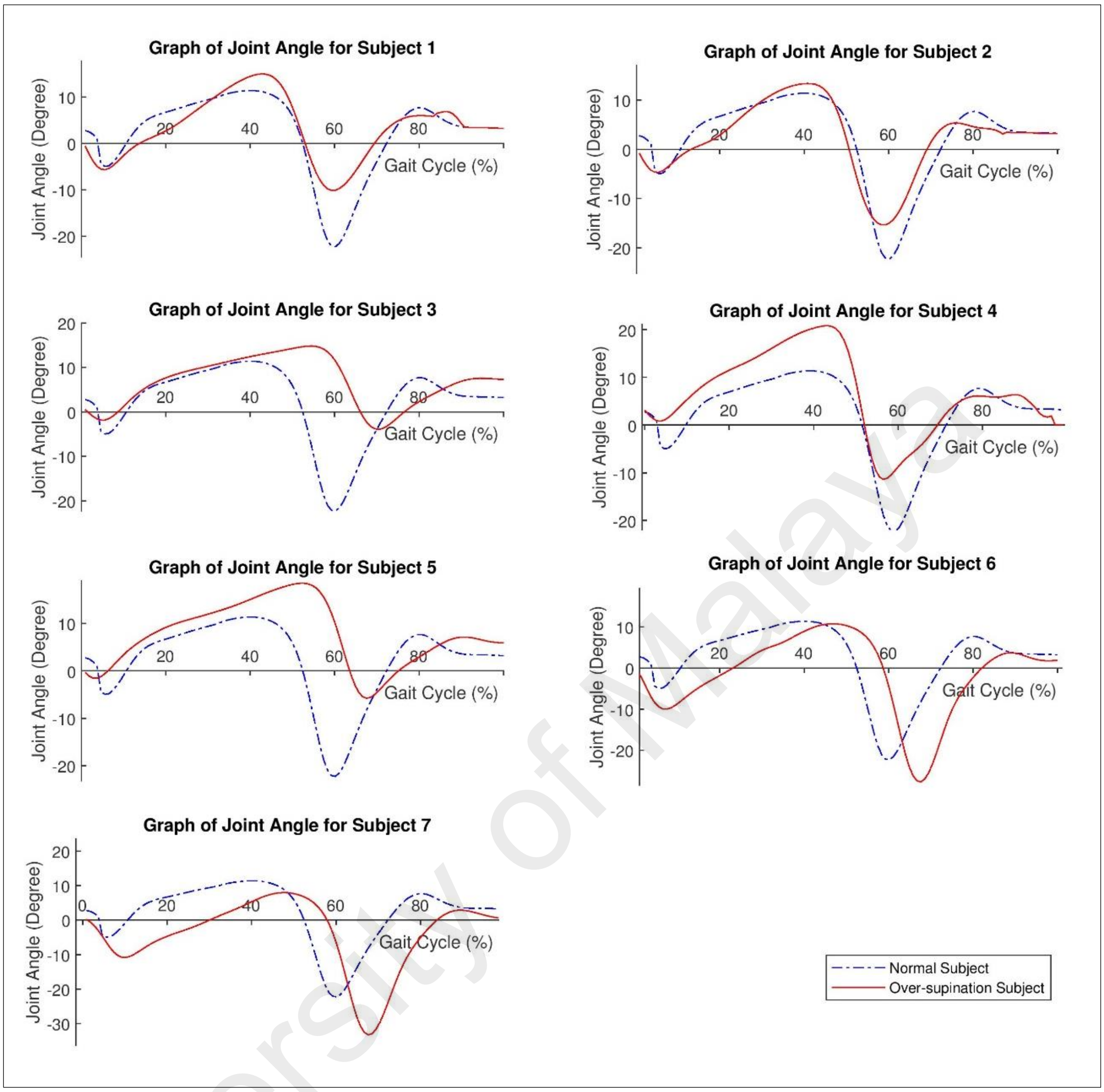


Figure 4.5: Graph of Ankle Angle for a complete gait cycle (100%) for each subjects (Dash dot blue line represent the Normal subject and red line represent Over-supination subject)

The kinematic motion of the foot and ankle begin at the heel strike phase. At this phase, the foot will normally supinate at the heel contact and the ankle moving into plantar flexion movement. As shown Table 4.3, Subjects with over-supination condition tends to be in plantar flexion condition during this part rather than in neutral position because the high arch put the foot in plantar flexion position such as subject 1(-0.69), subject 3 (-0.33°), subject 5 (-0.38°) and subject 7 (-4.55°). While the normal subject starts this phase at neutral position (0°) and a little dorsiflexion (2.97°). There were no rotation movement at the ankle during this movement and the foot was in process to accept the body weight. This support by the study by (Baines, Schwab, & Van Soest, 2018) that say that energy were being absorbed during the heel strike and no rotation happened during this phase.

Second phase was at the foot flat, the foot will pronate to adapt and support the surface and the ankle will move from plantar flexion to dorsiflexion over a fixed foot. Third phase was mid-stance where foot was at neutral position and ankle move to 10° dorsiflexion movement (Ota, Ueda, Aimoto, Suzuki, & Sigward, 2014). During the dorsiflexion movement over supination shows higher values of the dorsiflexion, this happened because the foot cannot flat properly and does not pronate to adapt the support surface. Normal subjects show 9.88° and 10.07° of dorsiflexion angle during this phase. While in over supination subjects the dorsiflexion angle in mid-stance are in the range of 10.20° - 15.36° dorsiflexion angle.

Fourth phase was heel off, the foot will supinate as foot becomes rigid to push off and ankle wills dorsiflexion 15° toward plantar flexion. Both normal subjects show the angle of 12.07° and 14.28° which was close to the reference value. While over supination subjects shows value higher than 15° especially subject 4 which was 22.48°. Lastly, toe off phase the foot will supinate and ankle move to 20° plantar flexion (Buldt et al., 2015). In normal subjects, both shows angle of -23.90° and -14.18° compare to over supination subjects that shows range of -3.11° until -26.14° angle. Subjects 3 show the lowest plantar flexion angle which was -3.11°. This maybe because foot already in supination position and support the plantar flexion already. Study by (Donatelli & Therapy, 1987) shows that over-supination will have inability to do pronation action and at the heel strike the foot should be in neutral and pronate immediately but in over supination condition the foot might remain supinated throughout the stance phase or pronates late in stance. Statistical analysis between normal groups with over supination shows the p value of 0.7012 which was no significant different between two groups.

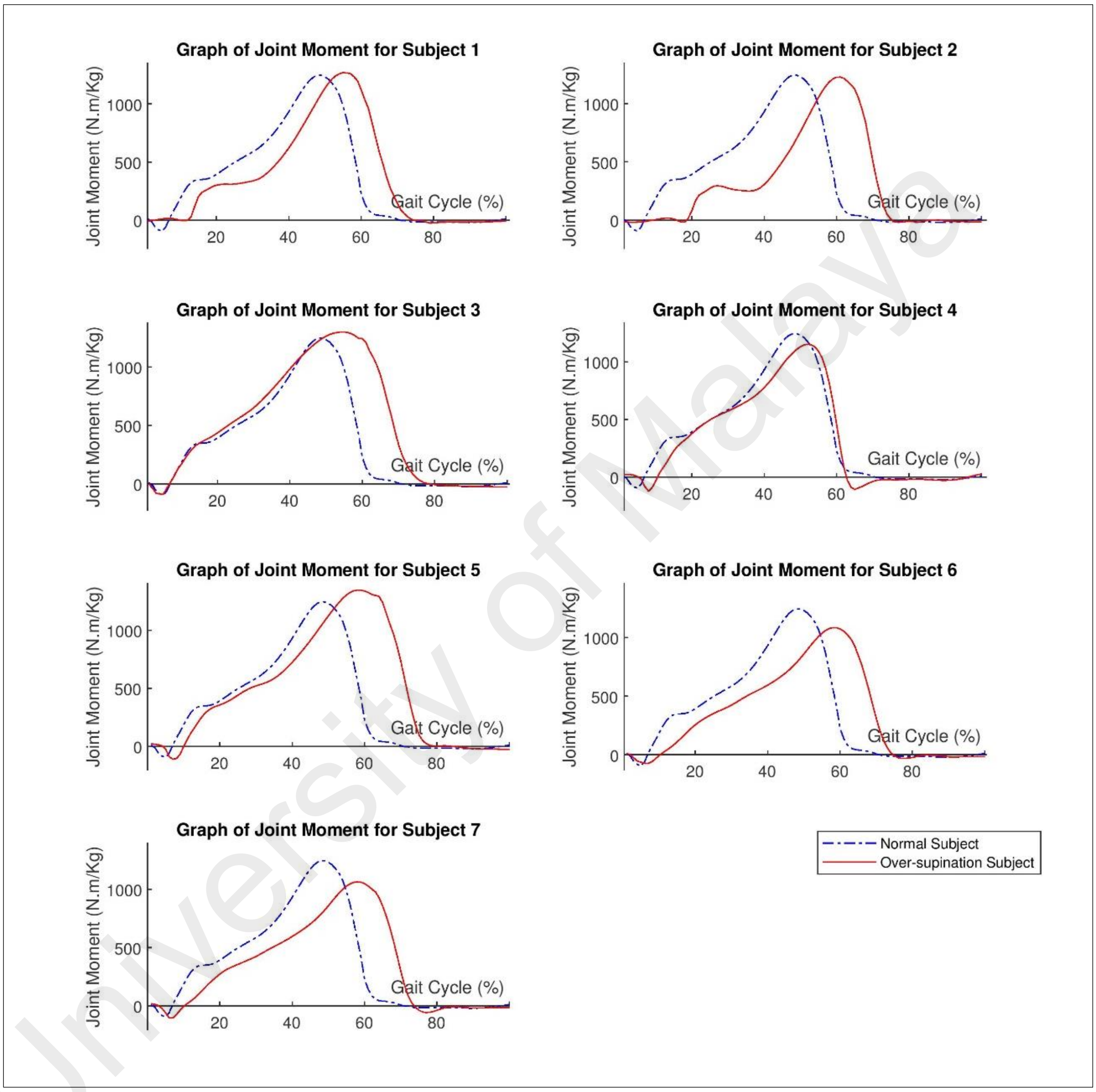


Figure 4.6: Graph of Ankle Joint Moment for a complete Gait cycle (100%) *A1 is the negative region of the y-axis and A2 is the positive region of y-axis (Dash dot blue line represent Normal subject and red line represent Over-supination subject)

The total moment at the joint was the product of two measurable quantities that were the joint segments moments of inertia and joints angular acceleration (Kuitunen, Komi, Kyrolainen, sports, & exercise, 2002). Then, the joint moment can be calculated if we minus the total moment with the ground reaction moment and joint reaction moment as shown in Figure 4.6. The negative region starts during heel strike, reaction force behind joint axis will show plantar flexion moment at heel strike. Then maximum plantar flexion moment continues at the foot flat. The reference value of moment during heel strike was -0.3. Normal subjects show values of -0.14N.m/kg and -0.10N.m/kg. While over supination subjects, they show range of value from -0.10N.m/kg until -0.18N.m/kg.

The moment of over supination subjects does not show many difference compare to normal subjects and the statistical analysis also support this as the p-value between this two groups was 0.9631 which indicated no significant difference. After that, positive region at the mid-stance due to slight dorsiflexion moment, at heel off the maximum dorsiflexion moment happened and it continue to toe off due to dorsiflexion moment. The value of joint moment in positive region for normal subjects were 0.87N.m/kg and 1.25N.m/kg, while for over-supination subjects the value in range of 1.06N.m/kg until 1.39N.m/kg. The p-values for all subjects were more than 0.05 which shows no significant difference of joint moment between normal and over-supination condition

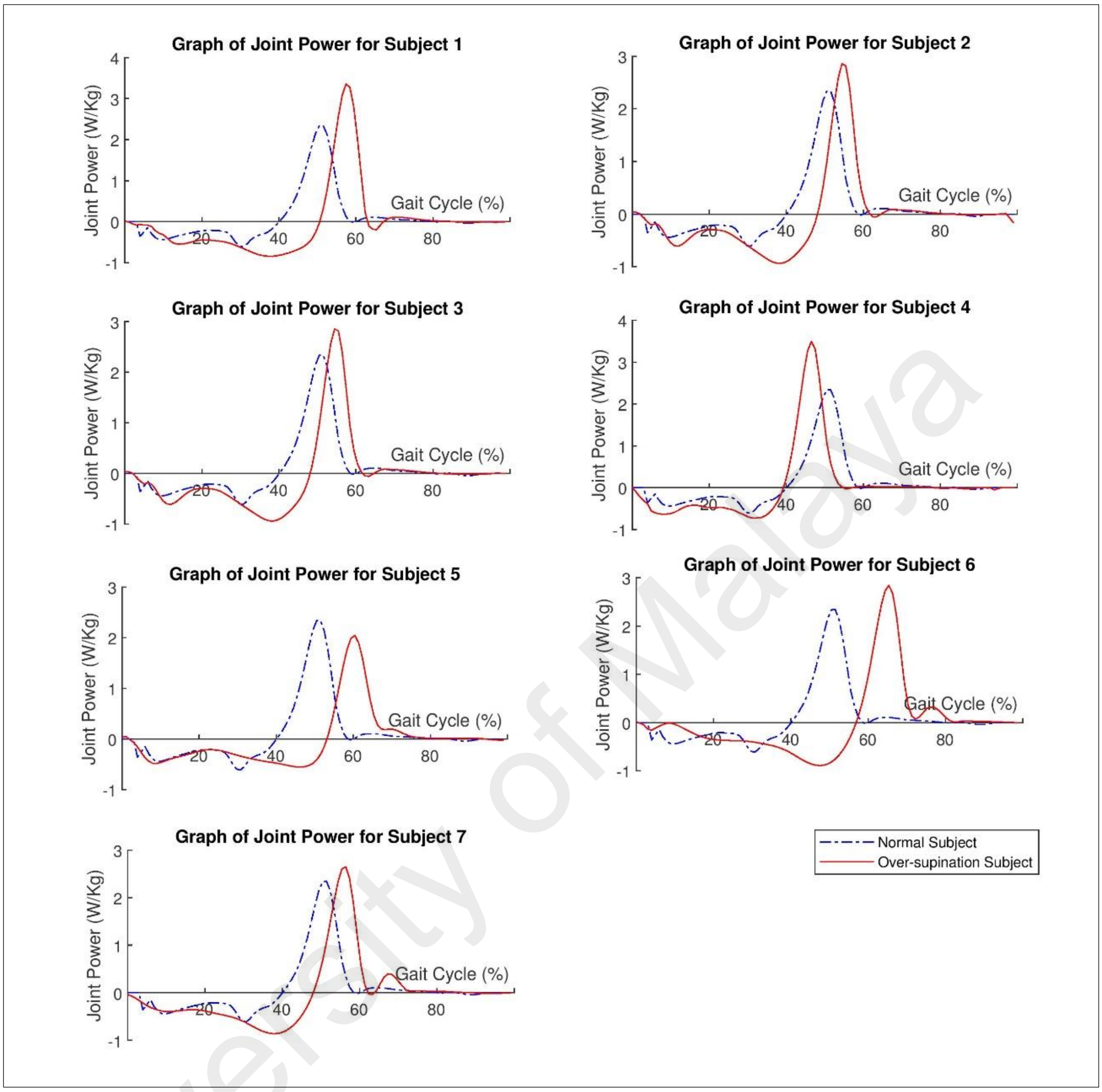


Figure 4.7:Graph of Ankle Joint Power for a complete Gait cycle (100%) for each subject (Dash dot blue line represent Normal subject and red line represent Over-supination subject)

Joint power was the product of joint moment and joint angular velocity. The A1 region was the negative region from Figure 4.7 and indicated that the energy was absorbed in eccentric muscle action and/or elongation of other soft tissue crossing the joint. While for the A2 region was consider positive region from Figure 4.7 and will indicate that the energy was generated by concentric action in muscles crossing the joint.

During heel strike, the joint power shows negative value because the muscle was contracting eccentrically to slow plantar flexion movement. This will continue in the foot flat condition as the muscle working eccentrically to control pronation movement. Then, at last phase of negative region was the mid-stance phase where plantar flexor muscle actively contracts eccentrically to dorsiflex the tibia and fibula over a fixed foot. As shown in Figure 4.7, the normal subjects both shows the joint power of -0.44W/kg and -0.57W/kg which were near to reference value of -0.5W/kg. While for over supination subjects, subject 2 shows higher power used which was -0.61W/kg and subject 6 shows less power used which was -0.16W/kg. This was because difference subject might have different composition muscle that helps them during movement because the net joint power measure were actually the power that produce by a group of muscle tendons using crossing a joint (Hamill, Gruber, & Derrick, 2014). Therefore, different subject might have different muscle tendons thus will differentiate the joint power.

The A2 region starts at the heel off where plantar flexion muscles begin to contract concentrically to prepare for push-off. Lastly, the positive region lasts at the toe off when plantar flexor muscle at peak activity but becoming inactive as foot move from the ground. As in Figure 4.7 the joint power of normal subjects are 2.37W/kg and 3.50W/kg which near to the reference value that was 3.5W/kg. While over-supination subjects mostly shows joint power values less than 3.5W/kg. Subject 3 shows the lower joint power which was 1.95W/kg. The lower joint power indicates that there were muscle that were not active during the movement since the foot in over-supination, thus proper treatment to return back the foot to normal condition was needed to ensure the muscle can be activate. From researcher (Ntousis, Mandalidis, Chronopoulos, Athanasopoulos, & posture, 2013) shows that the long term adapting of the soft tissue in over pronation and over-supination foot will cause the muscle activation change due tong term effect without treatment.

From the statistical analysis done for each subject to find the difference of ankle joint power between normal foot condition with over-supination condition to prove the null hypotheses which both normal and over-supination condition have same ankle joint power. From the analysis, the p-values for subjects 2, 3, 4 and 7 were less than α value which is 0.05. This indicates that there is a significant difference of joint power between normal foot conditions with over-supination condition thus the null hypothesis is rejected. In addition, there were two other subjects which were subject 1, subject 5 and subject 6 shows p-values more than 0.05 and accept the null hypotheses.

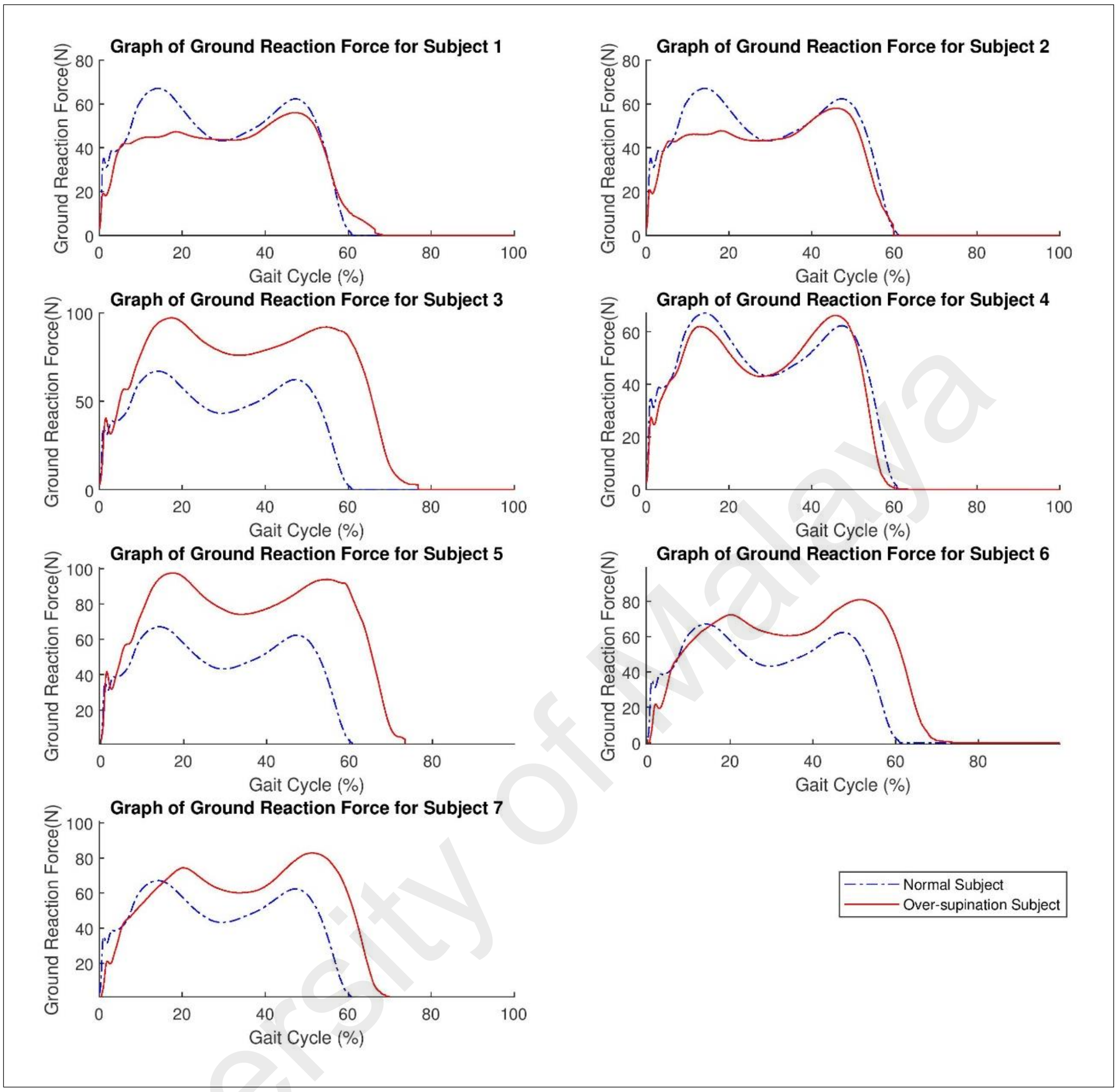


Figure 4.8: Graph of GRF for each subjects in a complete Gait cycle (100%) (Dash dot blue line represents Normal subject and red line represent Over-supination subject)

Kinetic parameter that being observed in this study in Ground Reaction Force (GRF). One of the researcher state in their study that a fundamental element of kinetic analyses of locomotion was GRF measurements (Burns, Deneweth Zendler, & Zernicke, 2019). One of the observed parameter was vertical component of force (Vertical GRF). The vertical GRF start at the heel strike and the force will be zero at the instant of contact with the ground. Then, the vertical force will continue to rise very steeply up to almost body weight in a fraction of a second. During flat foot, the body mass will continue to move downwards and landing on the leg. The instant for the subjects will show 12% of the body weight that being applied to the foot. From Figure 4.8, subjects 1 and 2 shows lowest value of GRF that are 480N and 489N which was only 4.8% of body weight applied to the foot.

Since the ankle were in over supination position, the body weight not fully supported by the ankle, knee joint might help to support the body weight in order maintain the stability. After that, the body will move to mid-stance phase where the upward motions of the body being decelerated and allowed to accelerate downward at the second half of the stance phase. At mid stance, 5.9% of body weight will be show and this acceleration allows a force of less than body weight to support the body. During this phase, subject 3 and 5 shows more than 5.9% body weight which were 761N and 741 N. Higher value of GRF at this phase might be due to impulsive loading as the foot ready to accelerated forward as stated by researcher (Pamukoff, Garcia, Holmes, & Post, 2019).

Then, at heel rise, the body mass will be accelerated forward and upwards ready for the stance phase of the other leg. This means that more than body weight will be required to support the body. It will show the 11% of the body weight on the vertical GRF. Lastly, the toe off was where contact with the ground was lost and the force will return to zero. If we can observe the GRF graph, there was spike that happened due to two-stage landing of the body on the ground. The vertical GRF graph was also known as M shape graph or double peak graph that show force relative to 100% of the body weight. From the statistical analysis using ANOVA test, p-value shows was more than 0.05 which show that there were no significant different between normal group and over supination group in term of their vertical GRF.

Table 4.3: Summary of ankle kinetic and kinematic parameter data for a complete gait cycle for Over-supination feet condition

| Parameters | | Ref | N1 | N2 | OS1 | OS2 | OS3 | OS4 | OS5 | OS6 | OS7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Angle ((IPH)) PF (–ve) /DF (+ve) | IC | 0 | 2.75 | 2.97 | -0.69 | 0 | -0.33 | 2.37 | -0.38 | 0.01 | -4.55 |
| | LR | -5 | -4.93 | -4.14 | -4.66 | -3.61 | -1.97 | 0.89 | -1.66 | -12.09 | -13.40 |
| | MSt | 10 | 9.54 | 9.88 | 11.61 | 11.78 | 12.75 | 15.36 | 12.83 | 10.20 | 10.91 |
| | TSt | 10 | 9.86 | 14.28 | 15.34 | 17.42 | 15.89 | 22.48 | 19.99 | 14.72 | 13.96 |
| | PSw | -20 | -22.24 | -14.18 | -16.11 | -18.63 | -3.11 | -12.28 | -6.49 | -24.33 | -26.14 |
| | ISw | -10 | -20.16 | -8.15 | -6.61 | -7.03 | -4.05 | -5.13 | -3.62 | -10.09 | -9.09 |
| | MSw | 5 | 7.69 | 5.39 | 6.67 | 6.26 | 8.11 | 6.59 | 6.63 | 0.32 | -2,29 |
| | TSw | 0 | 2.97 | 0 | 0 | -0.58 | 1.81 | 2.03 | 0 | -2.22 | -4.62 |
| Moment (kN.m/kg) PF (+ve /DF (-ve) | -ve region | -0.3 | -0.57 | -0.10 | -0.18 | -0.18 | -0.10 | -0.12 | -0.11 | -0.10 | -0.10 |
| | +ve region | 1.57 | 1.25 | 1.25 | 1.39 | 1.33 | 1.30 | 1.12 | 1.35 | 1.09 | 1.06 |
| Power (W/kg) | A1 region | -0.5 | -0.41 | -0.57 | -0.55 | -0.61 | -0.48 | -0.56 | -0.48 | -0.16 | -0.21 |
| | A2 region | 3.5 | 2.37 | 3.50 | 3.43 | 2.88 | 1.95 | 3.63 | 2.07 | 2.87 | 2.64 |
| GRF (N) | HS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Spike | 80 | 38.2 | 51.0 | 47.0 | 47.3 | 56.7 | 26.8 | 41.4 | 41.3 | 41.5 |
| | FP | 120 | 66.7 | 75.9 | 48.0 | 48.9 | 97.0 | 61.8 | 97.4 | 73.8 | 75.5 |
| | MSt | 59 | 43.2 | 52.2 | 42.0 | 41.2 | 76.1 | 43.0 | 74.1 | 58.9 | 58.8 |
| | SP | 110 | 62.2 | 70.6 | 55.6 | 56.0 | 91.9 | 66.2 | 93.7 | 82.7 | 82.1 |
| | Toe off | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*FP: First peak; SP: Second peak; OS: Over supination; N: Normal; Ref: Reference
PF: Plantarflexion; DF: Dorsiflexion (IC: Initial contact; LR: Loading response; MSt: Mid stance
TSt: Terminal stance;PSw: Pre swing; ISw: Initial Swing; MSw: Mid Swing; TSw: Terminal swig

# CHAPTER 5: CONCLUSSION & FUTURE WORK

This chapter concludes the overall findings of the research between the over-pronation and over-supination feet condition with normal feet condition during walking and also highlight the study limitation and future plan to improve this study.

## 5.1 Conclusion

As the conclusion, the main objective of this study that was to analyze the foot-ankle joint biomechanical behavior including the range of motion, joint moment, joint power and GRF in a complete gait cycle for all subjects in this study and to compare the foot-ankle biomechanical behavior between normal foot with over-pronation and over-supination foot during walking and provide data to assist future development of therapeutic devices.

For the over-pronation part, all the parameters analyzed in this study demonstrate that the over-pronation feet condition can lead to sustain ankle injuries and possibly ankle dislocation due to reduced efficiency during push-off phase and also due to insufficient dorsiflexion movement. The statistical analysis done shows that the p-values for joint angle of subjects 2, 3, 5, 6 and 7 were less than 0.05. This indicates that there is a significant difference of angle between normal feet condition with over-pronation condition thus the null hypothesis is rejected. But, there were two other subjects which were subject 1 and subject 4 shows p-values more than 0.05 and accept the null hypotheses.  While other parameters shows p-values less than 0.05 which indicates there is significance difference between over-pronation feet compare to normal feet condition.

While for over-supination feet condition demonstrated different kinetic and kinematic data, respectively for all the subjects with p-values more than 0.05 thus reject the entire null hypothesis that indicates that the means of all the groups were same.

Therefore, this research analyzed these kinetic and kinematic data to demonstrate that the ankle joint angle, moment, power and GRF does in fact influence by the condition of the feet and can cause deformities if no proper treatment was done. Thus, in the future development of therapeutic devices in the rehabilitation field in regards, to over-pronation and over-supination feet condition, should consider the parameters analyzed in this research to produce functional and effectively engineered therapeutic devices.

## 5.2 Study Limitation and Future Plan

Since in this study we have limited financial source to recruited more subjects for the experiment so hopefully in future, we can improve the analyses of the result by increase number of subjects and compare it by genders since female and male may have different type of gait pattern.

## LIST OF PUBLICATIONS AND PAPERS PRESENTED

Journal

1. N.S. Ghani, N.A Abd Razak, J. Usman, L. Benedict & H. Gholizadeh. (Forthcoming). Foot Over-Pronation Problem among Undergraduate Students: A Preliminary Study. (Accepted by Sains Malaysiana)
2. Nur Saibah Ghani , Nasrul Anuar Abd Razak, Juliana Usman and H. Gholizadeh. Biomechanics Investigation of Foot and Ankle Joint in Individual with Over-supination Foot: a preliminary study (Under review by Technology and Health care journal).

Proceeding

1. Nur Saibah Ghani, Nasrul Anuar Abd Razak, Juliana Usman, and Nur Afiqah Hashim (2018). Kinematic and Kinetic Parameters Analyses of Ankle Joint in Individuals with Flat Foot (Over Pronation). Poster presented at Asian Prosthetic & Orthotic Scientific Meeting 2018, Bangkok, Thailand.

**APPENDIX A**

**Subject consent form**

UNIVERSITY OF MALAYA

CPOE
Centre for Prosthetic & Orthotic Engineering
Rehabilitation & Research

Department of Biomedical Engineering (Prosthetics and Orthotics)

Patient/ Participant Consent Form

I hereby take part on a voluntary basis for the purpose of learning for KUEP______________________________ course which is held on the (date) _______________ . I understand the description of the procedures that have been explained by the demonstrator/student and agreed to authorize the process of clinical examination, fabrication and fitting of orthosis/prosthesis on myself . I also give permission to the demonstrator/students to use my personal information, pictures or videos for learning and educational purposes.

Participant's name:______________________________

IC number : ______________________________

HP number : ______________________________

Signature :

______________________________

## APPENDIX B

The Foot Posture Index Form

# *THE FOOT POSTURE INDEX©*
## *FPI-6*

**Reference Sheet**

The patient should stand in their relaxed stance position with double limb support. The patient should be instructed to stand still, with their arms by the side and looking straight ahead. It may be helpful to ask the patient to take several steps, marching on the spot, prior to settling into a comfortable stance position. During the assessment, it is important to ensure that the patient does not swivel to try to see what is happening for themself, as this will significantly affect the foot posture. The patient will need to stand still for approximately two minutes in total in order for the assessment to be conducted. The assessor needs to be able to move around the patient during the assessment and to have uninterrupted access to the posterior aspect of the leg and foot.

If an observation cannot be made (e.g. because of soft tissue swelling) simply miss it out and indicate on the datasheet that the item was not scored.

If there is genuine doubt about how high or low to score an item always use the more conservative score.

| **Rearfoot Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| Talar head palpation | Talar head palpable on lateral side/but not on medial side | Talar head palpable on lateral side/slightly palpable on medial side | Talar head equally palpable on lateral and medial side | Talar head slightly palpable on lateral side/ palpable on medial side | Talar head not palpable on lateral side/ but palpable on medial side |
| Curves above and below the malleoli | Curve below the malleolus either straight or convex | Curve below the malleolus concave, but flatter/ more shallow than the curve above the malleolus | Both infra and supra malleolar curves roughly equal | Curve below malleolus more concave than curve above malleolus | Curve below malleolus markedly more concave than curve above malleolus |
| Calcaneal inversion/eversion | More than an estimated 5° inverted (varus) | Between vertical and an estimated 5° inverted (varus) | Vertical | Between vertical and an estimated 5° everted (valgus) | More than an estimated 5° everted (valgus) |
| **Forefoot Score** | **-2** | **-1** | **0** | **1** | **2** |
| Talo-navicular congruence | Area of TNJ markedly concave | Area of TNJ slightly, but definitely concave | Area of TNJ flat | Area of TNJ bulging slightly | Area of TNJ bulging markedly |
| Medial arch height | Arch high and acutely angled towards the posterior end of the medial arch | Arch moderately high and slightly acute posteriorly | Arch height normal and concentrically curved | Arch lowered with some flattening in the central portion | Arch very low with severe flattening in the central portion – arch making ground contact |
| Forefoot abd/adduction | No lateral toes visible. Medial toes clearly visible | Medial toes clearly more visible than lateral | Medial and lateral toes equally visible | Lateral toes clearly more visible than medial | No medial toes visible. Lateral toes clearly visible |

*For further information, manuals and extra datasheets see: www.leeds.ac.uk/medicine/FASTER/FPI/*

## Foot Posture Index Datasheet

| **Patient name** | **ID number** |
|---|---|
| | |

| | *FACTOR* | *PLANE* | SCORE 1<br>Date_______________<br>Comment___________ | | SCORE 2<br>Date_______________<br>Comment___________ | | SCORE 3<br>Date_______________<br>Comment___________ | |
|---|---|---|---|---|---|---|---|---|
| | | | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* |
| Rearfoot | Talar head palpation | *Transverse* | | | | | | |
| | Curves above and below the lateral malleolus | *Frontal/ transverse* | | | | | | |
| | Inversion/eversion of the calcaneus | *Frontal* | | | | | | |
| Forefoot | Prominence in the region of the TNJ | *Transverse* | | | | | | |
| | Congruence of the medial longitudinal arch | *Sagittal* | | | | | | |
| | Abd/adduction forefoot on rearfoot | *Transverse* | | | | | | |
| | **TOTAL** | | | | | | | |

**Reference values**
*Normal = 0 to +5*
*Pronated = +6 to +9, Highly pronated 10+*
*Supinated = -1 to –4, Highly supinated –5 to -12*



## Foot Posture Index Datasheet

| **Patient name** | **ID number** |
|---|---|
| | |

| | *FACTOR* | *PLANE* | SCORE 1<br>Date_______________<br>Comment___________ | | SCORE 2<br>Date_______________<br>Comment___________ | | SCORE 3<br>Date_______________<br>Comment___________ | |
|---|---|---|---|---|---|---|---|---|
| | | | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* |
| Rearfoot | Talar head palpation | *Transverse* | | | | | | |
| | Curves above and below the lateral malleolus | *Frontal/ transverse* | | | | | | |
| | Inversion/eversion of the calcaneus | *Frontal* | | | | | | |
| Forefoot | Prominence in the region of the TNJ | *Transverse* | | | | | | |
| | Congruence of the medial longitudinal arch | *Sagittal* | | | | | | |
| | Abd/adduction forefoot on rearfoot | *Transverse* | | | | | | |
| | **TOTAL** | | | | | | | |

**Reference values**
*Normal = 0 to +5*
*Pronated = +6 to +9, Highly pronated 10+*
*Supinated = -1 to –4, Highly supinated –5 to -12*

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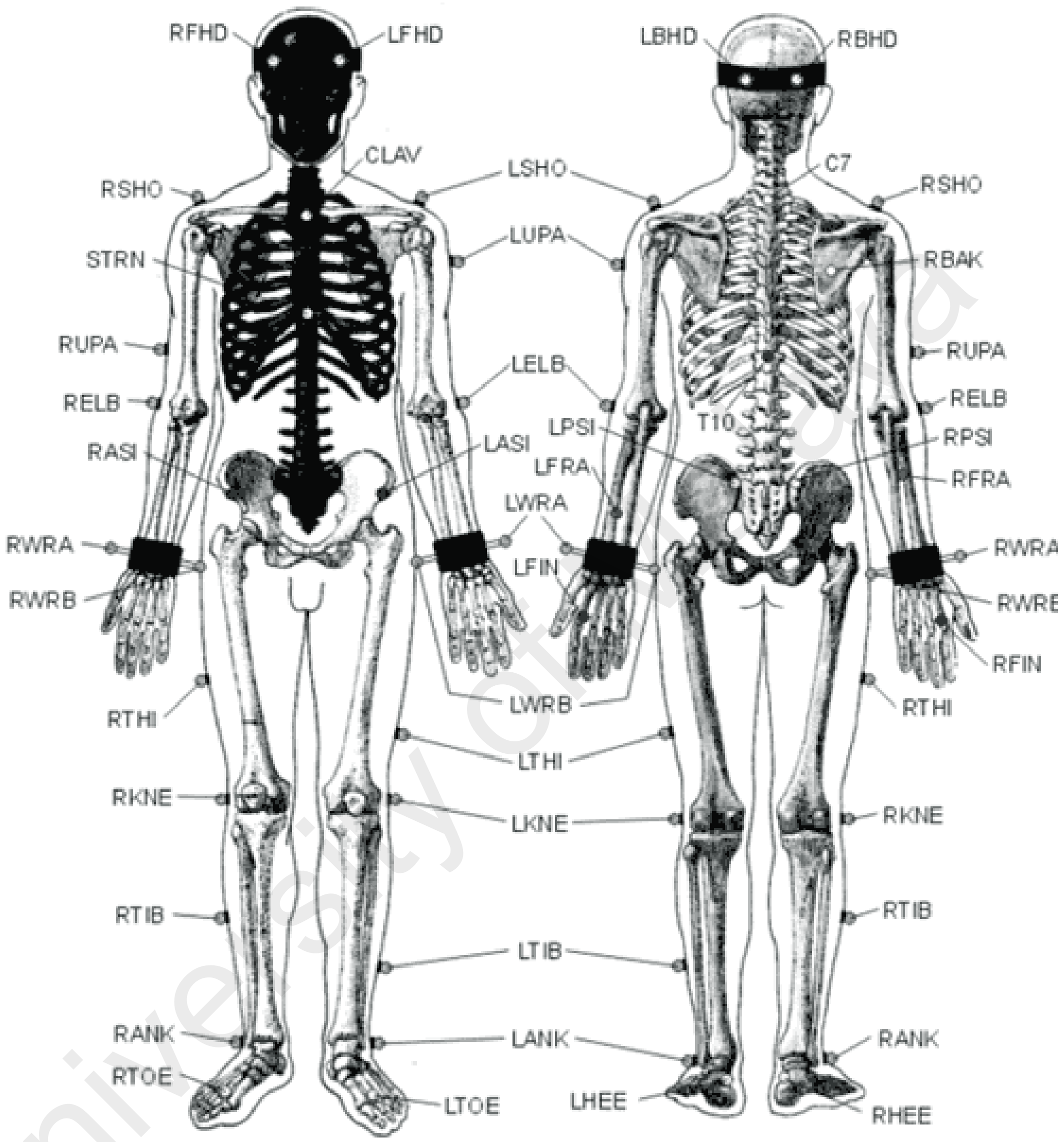
## APPENDIX C

The Helen Hayes market set placement



## CO-AUTHORS CONSENT

For candidates under the programme of PhD by Prior Publication.

Candidate must obtain the consent from other co-authors for all papers and/or manuscripts and/or publication that used as part of their PhD thesis.

It can be in form of a verification from the publisher or letter or email communication with the co-authors.

## REFERENCES

(IPH), I. f. P. H. (2015). National Health and Morbidity Survey 2015 (NHMS 2015) *Non-Communicable Diseases, Risk Factors & Other Health Problems* (Vol. 11).

Abu Osman, N. A., & Mohd Ismail, M. A. (2009). *Motion Analysis System*.

Aguilar, M. B., Abián-Vicén, J., Halstead, J., & Gijon-Nogueron, G. (2016). Effectiveness of neuromuscular taping on pronated foot posture and walking plantar pressures in amateur runners. *Journal of science and medicine in sport, 19*(4), 348-353.

Alam, M. N., Garg, A., Munia, T. T. K., Fazel-Rezai, R., & Tavakolian, K. (2017). Vertical ground reaction force marker for Parkinson's disease. *PloS one, 12*(5), e0175951.

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

Amendola, A., Lee, K.-B., Saltzman, C. L., & Suh, J.-S. (2007). Technique and early experience with posterior arthroscopic subtalar arthrodesis. *Foot & ankle international, 28*(3), 298-302.

Baines, P. M., Schwab, A., & Van Soest, A. J. P. o. (2018). Experimental estimation of energy absorption during heel strike in human barefoot walking. *13*(6), e0197428.

Bandholm, T., Boysen, L., Haugaard, S., Zebis, M. K., & Bencke, J. (2008). Foot medial longitudinal-arch deformation during quiet standing and gait in subjects with medial tibial stress syndrome. *The Journal of foot and ankle surgery, 47*(2), 89-95.

Banwell, H. A., Paris, M. E., Mackintosh, S., & Williams, C. M. (2018). Paediatric flexible flat foot: how are we measuring it and are we getting it right? A systematic review. *Journal of foot and ankle research, 11*(1), 21.

Barg, A., Tochigi, Y., Amendola, A., Phisitkul, P., Hintermann, B., & Saltzman, C. L. (2012). Subtalar instability: diagnosis and treatment. *Foot & ankle international, 33*(2), 151-160.

Brockett, C. L., & Chapman, G. J. (2016). Biomechanics of the ankle. *Orthopaedics and trauma, 30*(3), 232-238.

Buldt, A. K., Levinger, P., Murley, G. S., Menz, H. B., Nester, C. J., Landorf, K. B. J. G., & posture. (2015). Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet. *42*(1), 42-48.

Burns, G. T., Deneweth Zendler, J., & Zernicke, R. F. (2019). Validation of a wireless shoe insole for ground reaction force measurement. *Journal of sports sciences, 37*(10), 1129-1138.

Cain, L. E., Nicholson, L. L., Adams, R. D., & Burns, J. (2007). Foot morphology and foot/ankle injury in indoor football. *Journal of science and medicine in sport, 10*(5), 311-319.

Camargo, M. R., Barela, J. A., Nozabieli, A. J., Mantovani, A. M., Martinelli, A. R., & Fregonesi, C. E. (2015). Balance and ankle muscle strength predict spatiotemporal gait parameters in individuals with diabetic peripheral neuropathy. *Diabetes & Metabolic Syndrome: Clinical Research & Reviews, 9*(2), 79-84.

Chan, C. W., & Rudins, A. (1994). *Foot biomechanics during walking and running.* Paper presented at the Mayo Clinic Proceedings.

Charrette, M., & Overpronation, D. The Excessively Supinated Foot: Assessment and Treatment.

Dawe, E. J., & Davis, J. (2011). (vi) Anatomy and biomechanics of the foot and ankle. *Orthopaedics and Trauma, 25*(4), 279-286.

DeLisa, J. A. (1998). *Gait analysis in the science of rehabilitation* (Vol. 2): Diane Publishing.

Doherty, C., Bleakley, C., Hertel, J., Caulfield, B., Ryan, J., Sweeney, K., . . . Delahunt, E. (2016). Coordination and symmetry patterns during the drop vertical jump in people with chronic ankle instability and lateral ankle sprain copers. *Physical Therapy, 96*(8), 1152-1161.

Donatelli, R. J. J. o. O., & Therapy, S. P. (1987). Abnormal biomechanics of the foot and ankle. *9*(1), 11-16.

dos Santos, M. J., Gorges, A. L., & Rios, J. L. (2014). Individuals with chronic ankle instability exhibit decreased postural sway while kicking in a single-leg stance. *Gait & posture, 40*(1), 231-236.

Eizentals, P., Katashev, A., Okss, A., Pavare, Z., & Balcuna, D. (2019). *Detection of Excessive Pronation and Supination for Walking and Running Gait with Smart Socks.* Paper presented at the World Congress on Medical Physics and Biomedical Engineering 2018.

Fong, D. T.-P., Hong, Y., Shima, Y., Krosshaug, T., Yung, P. S.-H., & Chan, K.-M. (2009). Biomechanics of supination ankle sprain: a case report of an accidental injury event in the laboratory. *The American journal of sports medicine, 37*(4), 822-827.

Genova, J. M., & Gross, M. T. (2000). Effect of foot orthotics on calcaneal eversion during standing and treadmill walking for subjects with abnormal pronation. *Journal of Orthopaedic & Sports Physical Therapy, 30*(11), 664-675.

Gentili, A., Masih, S., Yao, L., & Seeger, L. (1996). Foot axes and angles. *the British Journal of radiology, 69*(826), 968-974.

Giannini, S., Faldini, C., Cadossi, M., Luciani, D., & Pagkrati, S. (2012). Surgical treatment of flexible flatfoot in adolescents with bioabsorbable implant *International Advances in Foot and Ankle Surgery* (pp. 367-376): Springer.

Golightly, Y. M., Hannan, M. T., Dufour, A. B., Hillstrom, H. J., & Jordan, J. M. (2014). Foot disorders associated with overpronated and oversupinated foot function: the Johnston County osteoarthritis project. *Foot & ankle international, 35*(11), 1159-1165.

Gunawardena, K. L., & Hirakawa, M. (2015). GestureTank: A gesture detection water vessel for foot movements. *International Journal on Advances in ICT for Emerging Regions, 8*(2), 1-11.

Hagen, M., Sanchez-Bergmann, D., Seidel, S., & Lahner, M. (2015). Angle-torque relationship of the subtalar pronators and supinators in younger and elderly males and females. *Journal of foot and ankle research, 8*(1), 64.

Hajirezaei, B., Mirzaei, S., & Khezri, A. (2017). The relationship between flat feet and cavus foot with body mass index in girl students. *International Journal of Applied Exercise Physiology, 6*(3), 15-22.

Hall, S. J. (1999). Basic Biomechanics WCB McGraw-Hill. *New York*.

Hamill, J., Gruber, A. H., & Derrick, T. R. (2014). Lower extremity joint stiffness characteristics during running with different footfall patterns. *European journal of sport science, 14*(2), 130-136.

Hintermann, B., & Nigg, B. M. (1998). Pronation in runners. *Sports medicine, 26*(3), 169-176.

Hisham, N. A. H., Nazri, A. F. A., Madete, J., Herawati, L., & Mahmud, J. (2017). *Measuring Ankle Angle and Analysis of Walking Gait using Kinovea*. Paper presented at the Johur, Malyasia: International Medical Device and Technology conference.

Jenkyn, T. R., Anas, K., & Nichol, A. (2009). Foot segment kinematics during normal walking using a multisegment model of the foot and ankle complex. *Journal of biomechanical engineering, 131*(3), 034504.

Kakihana, W., Torii, S., Akai, M., Nakazawa, K., Fukano, M., & Naito, K. (2005). Effect of a lateral wedge on joint moments during gait in subjects with recurrent ankle sprain. *American journal of physical medicine & rehabilitation, 84*(11), 858-864.

Karlsson, J., Eriksson, B. I., Bergsten, T., Rudholm, O., & Swärd, L. (1997). Comparison of two anatomic reconstructions for chronic lateral instability of the ankle joint. *The American journal of sports medicine, 25*(1), 48-53.

Keefe, D. T., & Haddad, S. L. (2002). Subtalar instability. Etiology, diagnosis, and management. *Foot and ankle clinics, 7*(3), 577-609.

Kernozek, T. W., & Ricard, M. D. (1990). Foot placement angle and arch type: effect on rearfoot motion. *Arch Phys Med Rehabil, 71*(12), 988-991.

Kluitenberg, B., Bredeweg, S. W., Zijlstra, S., Zijlstra, W., & Buist, I. (2012). Comparison of vertical ground reaction forces during overground and treadmill running. A validation study. *BMC musculoskeletal disorders, 13*(1), 235.

Ko, S.-u., Stenholm, S., Chia, C. W., Simonsick, E. M., & Ferrucci, L. (2011). Gait pattern alterations in older adults associated with type 2 diabetes in the absence of peripheral neuropathy—results from the Baltimore Longitudinal Study of Aging. *Gait & posture, 34*(4), 548-552.

Konradsen, L., & Voigt, M. (2002). Inversion injury biomechanics in functional ankle instability: a cadaver study of simulated gait. *Scandinavian journal of medicine & science in sports, 12*(6), 329-336.

Kosonen, J., Kulmala, J.-P., Müller, E., & Avela, J. (2017). Effects of medially posted insoles on foot and lower limb mechanics across walking and running in overpronating men. *Journal of biomechanics, 54*, 58-63.

Krähenbühl, N., Horn-Lang, T., Hintermann, B., & Knupp, M. (2017). The subtalar joint: a complex mechanism. *EFORT open reviews, 2*(7), 309-316.

Kuitunen, S., Komi, P. V., Kyrolainen, H. J. M., sports, s. i., & exercise. (2002). Knee and ankle joint stiffness in sprint running. *34*(1), 166-173.

Lange, B., Chipchase, L., & Evans, A. (2004). The effect of low-Dye taping on plantar pressures, during gait, in subjects with navicular drop exceeding 10 mm. *Journal of Orthopaedic & Sports Physical Therapy, 34*(4), 201-209.

Lee, J. S., Kim, K. B., Jeong, J. O., Kwon, N. Y., & Jeong, S. M. (2015). Correlation of foot posture index with plantar pressure and radiographic measurements in pediatric flatfoot. *Annals of rehabilitation medicine, 39*(1), 10.

Levangie, P., & Norkin, C. (2011). Joint structure and function: a comprehensive analysis FA Davis Company.

Lundberg, A. (1989). Kinematics of the ankle and foot: in vivo roentgen stereophotogrammetry. *Acta Orthopaedica Scandinavica, 60*(sup233), 1-26.

Malaysia, I. f. P. H. (2015). National Health & Morbidity Survey (NHMS 2015). Vol. II: Non-Communicable Diseases, Risk Factors & Other Health Problems: Institute for Public Health Malaysia Kuala Lumpur.

Marieb, E. N., & Hoehn, K. (2007). *Human anatomy & physiology*: Pearson education.

Martini, F., Timmons, M., & Tallitsch, R. (2014). Human Anatomy, 7th Editio: Pearson Inc.

McGowan, C. P., Baudinette, R. V., & Biewener, A. A. (2005). Joint work and power associated with acceleration and deceleration in tammar wallabies (Macropus eugenii). *Journal of Experimental Biology, 208*(1), 41-53.

Mitchell, A., Dyson, R., Hale, T., & Abraham, C. (2008). Biomechanics of ankle instability. Part 1: Reaction time to simulated ankle sprain. *Medicine and science in sports and exercise, 40*(8), 1515-1521.

Naser, S. S. A., & Mahdi, A. O. (2016). A proposed Expert System for Foot Diseases Diagnosis. *American Journal of Innovative Research and Applied Sciences, 2*(4), 155-168.

Nixon, S. A., Hanass-Hancock, J., Whiteside, A., & Barnett, T. (2011). The increasing chronicity of HIV in sub-Saharan Africa: Re-thinking" HIV as a long-wave event" in the era of widespread access to ART. *Globalization and health, 7*(1), 41.

Ntousis, T., Mandalidis, D., Chronopoulos, E., & Athanasopoulos, S. (2013). EMG activation of trunk and upper limb muscles following experimentally-induced overpronation and oversupination of the feet in quiet standing. *Gait & posture, 37*(2), 190-194.

Ntousis, T., Mandalidis, D., Chronopoulos, E., Athanasopoulos, S. J. G., & posture. (2013). EMG activation of trunk and upper limb muscles following experimentally-induced overpronation and oversupination of the feet in quiet standing. *37*(2), 190-194.

Oleksy, Ł., Mika, A., Łukomska-Górny, A., Marchewka, A., & Machines, Z. (2010). Intrarater reliability of the Foot Posture Index (FPI-6) applied as a tool in foot assessment in children and adolescents. *Medical Rehabilitation, 14*(4), 18-28.

Ota, S., Ueda, M., Aimoto, K., Suzuki, Y., & Sigward, S. (2014). Acute influence of restricted ankle dorsiflexion angle on knee joint mechanics during gait. *The Knee, 21*(3), 669-675.

Pamukoff, D., Garcia, S., Holmes, S., & Post, B. (2019). Association between ground reaction force characteristics during gait and knee injury and osteoarthritis outcome scores in young adults with obesity. *Osteoarthritis and Cartilage, 27*, S133-S134.

Paul, L., Ellis, B., Leese, G., McFadyen, A., & McMurray, B. (2009). The effect of a cognitive or motor task on gait parameters of diabetic patients, with and without neuropathy. *Diabetic Medicine, 26*(3), 234-239.

Phan, C.-B., Nguyen, D.-P., Lee, K.-M., & Koo, S. (2018). Relative movement on the articular surfaces of the tibiotalar and subtalar joints during walking. *Bone & Joint Research, 7*(8), 501-507.

Plan, E. T., & Khandani, S. (2005). Engineering design process.

Redmond, A. C., Crane, Y. Z., & Menz, H. B. (2008). Normative values for the foot posture index. *Journal of foot and ankle research, 1*(1), 6.

Riegger, C. (1802). Anatomy of Foot and Ankle. *Physical Therapy, 1814*.

Ringleb, S. I., Dhakal, A., Anderson, C. D., Bawab, S., & Paranjape, R. (2011). Effects of lateral ligament sectioning on the stability of the ankle and subtalar joint. *Journal of orthopaedic research, 29*(10), 1459-1464.

Riskowski, J. L., Dufour, A. B., Hagedorn, T. J., Hillstrom, H. J., Casey, V. A., & Hannan, M. T. (2013). Associations of foot posture and function to lower extremity pain: results from a population-based foot study. *Arthritis care & research, 65*(11), 1804-1812.

Rome, K., & Brown, C. (2004). Randomized clinical trial into the impact of rigid foot orthoses on balance parameters in excessively pronated feet. *Clinical rehabilitation, 18*(6), 624-630.

Ryu, H. X., & Park, S. (2018). Estimation of unmeasured ground reaction force data based on the oscillatory characteristics of the center of mass during human walking. *Journal of biomechanics, 71*, 135-143.

Sabharwal, R., & Singh, S. (2017). Prevalence of ankle instabilities and disabilities among female Kathak dancers. *Physiotherapy-The Journal of Indian Association of Physiotherapists, 11*(2), 45.

Shih, Y.-F., Wen, Y.-K., & Chen, W.-Y. (2011). Application of wedged foot orthosis effectively reduces pain in runners with pronated foot: a randomized clinical study. *Clinical rehabilitation, 25*(10), 913-923.

Simkin, A., Leichter, I., Giladi, M., Stein, M., & Milgrom, C. (1989). Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot & ankle, 10*(1), 25-29.

Snook, A. G. (2001). The relationship between excessive pronation as measured by navicular drop and isokinetic strength of the ankle musculature. *Foot & ankle international, 22*(3), 234-240.

Wang, H., & Brown, S. R. (2017). The effects of total ankle replacement on ankle joint mechanics during walking. *Journal of Sport and Health Science, 6*(3), 340-345.

Willems, T., Witvrouw, E., Delbaere, K., De Cock, A., & De Clercq, D. (2005). Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait & posture, 21*(4), 379-387.

Wright, I. C., Neptune, R. R., Van Den Bogert, A. J., & Nigg, B. M. (2000). The effects of ankle compliance and flexibility on ankle sprains. *Medicine and science in sports and exercise, 32*(2), 260-265.

Xiao, J., Zhang, Y., Zhao, S., & Wang, H. (2017). Measuring the 3D motion space of the human ankle. *Technology and Health Care, 25*(S1), 219-230.

Zang, X., Liu, X., Liu, Y., Iqbal, S., & Zhao, J. (2016). Influence of the swing ankle angle on walking stability for a passive dynamic walking robot with flat feet. *Advances in Mechanical Engineering, 8*(3), 1687814016642018.