T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL
THE DEPARTMENT OF BIOMEDICAL ENGINEERING
MASTER’S PROGRAM IN BIOMEDICAL ENGINEERING

COMPARATIVE STUDY OF STEP-TO-STEP VARIABILITY IN ADULTS WITH FLATFOOT AND NORMAL ARCHES DURING TREADMILL GAIT

MASTER’S THESIS

BILAL AYAD GHAZI GHAZI

ISTANBUL 2025

T.C.

BAHCESEHIR UNIVERSITY

GRADUATE SCHOOL

THE DEPARTMENT OF BIOMEDICAL ENGINEERING

MASTER’S PROGRAM IN BIOMEDICAL ENGINEERING

COMPARATIVE STUDY OF STEP-TO-STEP VARIABILITY IN ADULTS WITH FLATFOOT AND NORMAL ARCHES DURING TREADMILL GAIT

MASTER’S THESIS

BILAL AYAD GHAZI GHAZI

THESIS ADVISOR

ASSIST. PROF. BURCU TUNÇ ÇAMLIBEL

ISTANBUL 2025

T.C.

BAHÇEŞEHİR UNIVERSITY
GRADUATE SCHOOL

11/04/2025

MASTER THESIS APPROVAL FORM

Program Name:	Biomedical Engineering
Student's Name and Surname:	BILAL AYAD GHAZI GHAZI
Name of the Thesis:	COMPARATIVE STUDY OF STEP-TO-STEP VARIABILITY IN ADULTS WITH FLATFOOT AND NORMAL ARCHES DURING TREADMILL GAIT
Thesis Defense Date	11/ 04 / 2025

This thesis has been approved by the Graduate School, which has fulfilled the necessary conditions as a master's thesis.

Assoc. Prof. Yücel Batu SALMAN
Institute Director

This thesis was read by us; quality and content as a master's thesis have been seen and accepted as sufficient.

	Title, Name	**Institution**	**Signature**
Thesis Advisor:	Assist. Prof. Burcu TUNÇ ÇAMLIBEL	Bahçeşehir University	
2nd Member	Assist. Prof. Bora BÜYÜKSARAÇ	Bahçeşehir University	
3rd Member (Out-side Institution)	Assist. Prof. Mustafa Erkam ÖZATEŞ	Turkish German University	

I hereby declare that all information in this document has been obtained and presentedin accordance with academic rules and ethical conduct. I also declare that, as requiredby these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Bilal Ayad Ghazi Ghazi

Signature:

ABSTRACT

COMPARATIVE STUDY OF STEP-TO-STEP VARIABILITY IN ADULTS WITH FLATFOOT AND NORMAL ARCHES DURING TREADMILL GAIT

Ghazi Bilal Ayad Ghazi
Biomedical Engineering Master's Program
Thesis supervisor: Assist. Prof. Burcu Tunç Çamlıbel

April 2025, 59 pages

This study investigates the biomechanical difference between flatfeet and normal arched subjects during walking and jogging, with specific reference to plantar pressure distribution and gait variation. 21 subjects (9 flatfeet, 12 normal arches) performed standardized walking and jogging trials wearing in-shoe pressure measurement system (Pedar-X). Plantar pressure measurements were taken at 100 Hz and analysed across six anatomical regions of the foot: hindfoot, medial midfoot, lateral midfoot, forefoot, toes, and hallux.

Spatiotemporal gait parameters and variability were also assessed. A 2×2×6 mixed-model RM-ANOVA with group (Flatfoot vs. Normal), speed (Walk vs. Jog), and region (6-foot regions) as factors was conducted on both peak and mean plantar pressure.

Results revealed distinct patterns of pressure distribution between foot types, with flatfeet participants having significantly more pressure in the lateral midfoot region during walking ($p=0.001$) and jogging ($p<0.001$), while normal arched participants had more pressure in the forefoot and hallux regions, particularly in jogging ($p<0.001$). Mixed-model ANOVA revealed significant group ($F=8.22$, $p=0.004$), speed ($F=19.38$, $p<0.001$), and region ($F=100.14$, $p<0.001$) main effects and significant interactions between factors. Although pressure distribution varied, Spatiotemporal gait parameters did not show statistically significant differences between groups; nevertheless, swing time variability for walking yielded medium to large effect sizes.

These findings enhance our understanding of the biomechanical relevance of foot arch shape and provide valuable information for clinical assessment, shoe design, and injury prevention strategies for patients with different foot types.

Keywords: Flatfeet,Plantar pressure,Gait analysis, Pedar-X, Center Of Pressure.

ÖZET

DÜZ TABANLI VE NORMAL ARK YAPISINA SAHIP YETIŞKINLERDE KOŞU BANDINDA YÜRÜYÜŞ SIRASINDAKI ADIMDAN ADIMA DEĞIŞKENLIĞIN KARŞILAŞTIRMALI İNCELENMESI

Bilal Ayad Ghazi Ghazi
Biyomedikal Mühendisliği Yüksek Lisans Programı
Tez Danışmanı: Dr. Öğr. Üyesi Burcu Tunç Çamlıbel

Nisan 2025, 59 sayfa

Bu çalışma, düz tabanlı ve normal arklı bireyler arasında yürüyüş ve koşu sırasındaki biyomekanik farkı, özellikle plantar basınç dağılımı ve yürüyüş değişkenliğine odaklanarak incelemektedir. Yirmi bir denek (9 düz tabanlı, 12 normal arkli), ayakkabı içi basınç ölçüm sistemi (Pedar-X) giyerek standartlaştırılmış yürüme ve koşma denemeleri gerçekleştirmiştir. Plantar basınç ölçümleri 100 Hz'te alınmış ve ayağın altı anatomik bölgesi (topuk, medial orta ayak, lateral orta ayak, ön ayak, parmaklar ve halluks) boyunca analiz edilmiştir. Uzamsal-zamansal yürüyüş parametreleri ve değişkenliği de değerlendirilmiştir. Hem tepe hem de ortalama plantar basınç üzerinde Grup (Düz Taban vs. Normal), Hız (Yürüme vs. Koşu) ve Bölge (6 ayak bölgesi) faktörleri ile 2 × 2 × 6 karma model tekrarlı ölçümler ANOVA (RM-ANOVA) uygulanmıştır. Sonuçlar, ayak tipleri arasında belirgin basınç dağılımı örüntüleri ortaya koymuştur; düz tabanlı katılımcılar yürüyüş ($p=0{,}001$) ve koşu ($p<0{,}001$) sırasında lateral orta ayak bölgesinde anlamlı derecede daha fazla basınca sahipken, normal arkli katılımcılar özellikle koşu sırasında ön ayak ve halluks bölgelerinde daha fazla basınca sahip olarak değerlendirilmiştir ($p<0{,}001$). Karma model ANOVA, anlamlı Grup ($F=8{,}22$, $p=0{,}004$), Hız ($F=19{,}38$, $p<0{,}001$) ve Bölge ($F=100{,}14$, $p<0{,}001$) ana etkilerini ve faktörler arasında anlamlı etkileşimleri ortaya çıkarmıştır. Basınç dağılımı farklılık gösterse de, uzamsal-zamansal yürüyüş parametreleri gruplar arasında istatistiksel olarak anlamlı farklar göstermemiştir; bununla birlikte, yürüme için salınım zamanı değişkenliği orta ila büyük etki büyüklükleri vermiştir. Bu bulgular, ayak arkı şeklinin biyomekanik önemine dair anlayışımızı geliştirmekte ve farklı ayak tiplerine sahip hastalar için klinik değerlendirme, ayakkabı tasarımı ve yaralanma önleme stratejileri açısından değerli bilgiler sağlamaktadır.

Anahtar Kelimeler: Düz tabanlık, Plantar basınç, Yürüyüş analizi, Pedar-X, Basınç merkezi.

ACKNOWLEDGMENTS

I am deeply indebted to my thesis supervisor, Dr. Burcu Tunç Çamlıbel. I am incredibly grateful for her exceptional guidance, patience, and the continuous support she offered me throughout this research process. Her insights and mentorship were pivotal in shaping this thesis and my development as a researcher.

My heartfelt appreciation goes to my wonderful family – my parents and siblings. Thank you for always believing in me, for your endless encouragement, and for being my pillars of strength, especially when challenges arose. Your love and support mean the world to me.

I also want to thank my friends for the much-needed encouragement and shared moments that made this journey less daunting. A particular thank you is reserved for everyone who participated in my experiments – this thesis could not have been completed without your generous contribution and willingness to help.

TABLE OF CONTENTS

ETHICAL CONDUCT iii

ABSTRACT iv

ÖZET vi

ACKNOWLEDGMENTS viii

LIST OF TABLES xi

LIST OF FIGURES xiii

Chapter 1 Introduction 1

- 1.1 Background 1
- 1.2 Statement Of The Problem 3
- 1.3 Purpose Of The Study 3
- 1.4 Research Questions 4
- 1.5 Definitions 5

Chapter 2 Literature Review 8

- 2.1 Structure And Function Of The Foot 8
- 2.2 Introduction To Flatfoot 9
- 2.3 Assessment Methods For Flatfoot 10
- 2.4 Effect Of Flatfoot 10
- 2.5 Common Approaches For Correcting Flatfoot 11

Chapter 3 Methodology 14

- 3.1 Research Participants 14
- 3.2 Procedures 15
  - 3.2.1. Data Collection Instruments 16
  - 3.2.2. Data Collection Procedures 21
  - 3.2.3. Data Analysis Procedures 23

Chapter 4 Results 32

- 4.1 Participants Characteristic 32
- 4.2 Statistical Approach 33

4.3 Spatiotemporal Gait Parameters And Step-To-Step Variability 34
4.3.1 Mean Gait Cycle Durations 34
4.3.2 Stance And Swing Phases 36
4.3.3 Step-To-Step Time Variability 40
4.4 Center Of Pressure (Cop) Trajectory And Path Metrics 41
4.4.1 Cop Path Length 41
4.4.2 Cop Trajectory Pattern 43
4.5 Regional Plantar Pressure Distribution 45
4.5.1 Peak Pressure Comparisons Between Groups 45
4.5.2 Mean Pressure Comparisons Between Groups 47
4.5.3 Within-Group Comparisons Between Walking And Jogging 48
Chapter 5 Discussion 53
5.1 Plantar Pressure Distribution Patterns 53
5.2 Spatiotemporal Parameters And Variability 55
5.3 Center Of Pressure Trajectory 57
Chapter 6 Conclusion, Limitations & Future Work 58
6.1 Conclusion 58
6.2 Limitation 59
REFERENCES 60
APPENDICES 66
Supplementary Statistical Analyses 67
A.1 Complete Anova Results For Plantar Pressure Analysis 67
A.2 Effect Size Calculations 70
Normalized Plantar Pressure Data 72
Representative Pressure Distribution Patterns 74

LIST OF TABLES

TABLES

Table 1 Pedar-X Sensor Number Distribution Across Foot Regions 29

Table 2 Participant Demographic Characteristics 32

Table 3 Step And Stride Time Measures During Walking (Flatfoot Vs. Normal Arch) 34

Table 4 Step And Stride Time Measures During Jogging (Flatfoot Vs. Normal Arch) 35

Table 5 Mean Stance Time And Swing Time For Both Flatfeet And Normal Arched Participants During Walking And Jogging (Left And Right Limbs). 37

Table 6 The Mean And Standard Deviation Of The Coefficient Of Variation For Step 40

Table 7 Mean And Standard Deviation Of Cop Path Length During Walking And Jogging For Both Groups (Left And Right Limbs)... 42

Table 8 Mean And Sd For Mid-Stance Cop Location (X And Y Coordinates) For Left Foot During Walking And Jogging For Both Groups. 43

Table 9 Mean And Sd For Mid-Stance Cop Location (X And Y Coordinates) For Right Foot During Walking And Jogging For Both Groups. 44

Table 10 Mean Peak Pressure Values (Kpa/Kg) By Foot Region, Group, And Activity 46

Table 11 Mean Pressure Values (Kpa/Kg) By Foot Region, Group, And Activity ... 47

Table 12 Summary Of Anova Results For Main Effects And Interactions. 49

Table 13 Effect Sizes For Spatiotemporal Parameters 55

Table 14 Complete Mixed-Model Anova Results For Peak Pressure (Kpa/Kg) 68

Table 15 Complete Mixed-Model Anova Results For Mean Pressure (Kpa/Kg) 69

Table 16 Cohen's D Effect Sizes For Between-Group Comparisons Of Peak Pressure 71

Table 17 Normalized Peak Pressure Values (Mean ± Sd) By Foot Region, Group, And Activity 72

Table 18 Normalized Mean Pressure Values (Mean ± Sd) By Foot Region, Group, And Activity 73

Table 19 Percent Change In Normalized Peak Pressure From Walking To Jogging 74

LIST OF FIGURES

FIGURES

Figure 1 Walking Cycle (Https://Creativecommons.Org/Licenses/By-Sa/4.0, Via Wiki-Media Commons.) 6
Figure 2 Running Cycle (Https://Creativecommons.Org/Licenses/By-Sa/4.0, Wiki-Media Commons.). 6
Figure 3 Normal Foot Vs Flat Foot (Boyne Clinic Https://Boynerclinic.Com/Pes-Planus-Flat-Feet/, Via Boyner Clinic.) 7
Figure 4 Foot Bones (Anon N.D.) 8
Figure 5 Navicular Drop Test (Menz 1998). 14
Figure 6 The Pedar-X Foot Pressure Measurement System (Novel Gmbh) 16
Figure 7 Position Of The Pedar-X Signal Transmitter On The Participant's Lower Back. 17
Figure 8 Participant's Side View 18
Figure 9 Motorized Treadmill Used In The Study, Model (Ultima Dc-1500). 19
Figure 10 Decathlon Basketball Vp-500 Fit Athletic Footwear Used In The Experiment. 20
Figure 11 A Millimetre-Marked Ruler Used For Navicular Drop Measurement. 21
Figure 12 Comparison Of Total Raw And Filtered Foot Pressure 25
Figure 13 Gait Event Detection From In-Shoe Pressure Data 26
Figure 14 Normalized Trajectories For Selected Foot Stances Example. 30
Figure 15 Step Time And Stride Time Mean For Both Conditions During Walking And Jogging. 36
Figure 16 Mean Stance Time During Walking And Jogging For Both Groups (Left And Right Limbs) With Error Bars. 38
Figure 17 Mean Swing Time During Walking And Jogging For Both Groups (Left And Right Limbs) With Error Bars. 39
Figure 18 Cop Path Length By Foot Type And Limb During Jogging And Walking 43
Figure 19 Mediolateral (X) Cop Position By Foot Type, Condition, And Limb 44
Figure 20 Anteroposterior (Y) Cop Position By Foot Type, Condition, And Limbs. 45
Figure 21 Mean Peak Pressure Distribution Lines Between Flatfeet And Normal Arched Participants During Walking And Jogging 46

Figure 22 Mean Plantar Pressure For Both Flatfeet And Normal Arched Participants During Walking And Jogging. 48

Chapter 1

Introduction

With both propulsive and shock-absorbing qualities, the foot has an extremely flexible structure. It improves the efficiency of locomotion and lowers impact forces by functioning like a spring. The medial longitudinal arch flattens (pronation) at mid-stance of locomotion, allowing ligaments and tendons to extend, therefore helping shock absorption by storing elastic energy. The arch now recoils as the foot supinates in late stance, releasing the accumulated energy to help in push-off. This cyclic mechanism acts both as a shock absorber and a rigid lever during the gait cycle, allowing the foot to efficiently distribute stresses, protect the lower extremities, and act both as a shock absorber and a rigid lever (Babu and Bordoni 2025).

Key structural element is the foot arch, which consists of longitudinal and transverse arches. Supporting the longitudinal arch are key skeletal bones such as calcaneus, talus, navicular, first cuneiform, and first metatarsal. In comparison, the transverse arch consists of the navicular and three cunea bones. The junction of these two arches not only provides a cushioning effect but also lets the foot fit to different types of terrain, hence offering notable structural support. The arch of the foot plays a crucial role in load distribution and functions as a ground-impact force-dispersing absorber (Standring 2016). Arches and the surrounding soft tissues enable the distribution of body mass support and plantar pressure. Specifically, the medial longitudinal arch builds a robust and stiff framework able to support the whole body in weight-bearing activities. Studies show that those with lower and higher arches had more equal pressure distribution. This causes increased midfoot loading and less peak pressure along the foot. in the heel and forefoot regions (Stolwijk et al. 2013).

1.1 Background

Human beings rely on a series of transmissions of force across the lower limb joints to carry out basic movements, such as ambulation, running, and jumping. The foot, being a critical component of lower limb anatomy, comes into direct contact with the ground in various activities, supporting the weight from both the upper body and the legs in combination with the ground reaction force.

It plays a vital role in attenuating resultant impacts and vibrations, essentially acting as the shock absorber of the body. In the past, a considerable percentage of people who had flat feet either remained unaware of their condition or chose not to pursue corrective interventions or seek remedies for it due to the lack of visible symptoms or pain. This unawareness resulted in prolonged durations of abnormal gait and running mechanics compared to those without such ailments, thus predisposing them to discomfort in the knees and lower back. Nowadays, rapid progress in the fields of sports biomechanics and sports medicine has developed greater public interest in, as well as knowledge about, foot health, and as such, more widespread research into flat foot biomechanics (Banwell, Mackintosh, and Thewlis 2014).

Flat foot, or pes planus, is a common deformity of the foot where there is a loss the medial longitudinal arch is a flexible structure made of contractile tissue, which consists of bones, muscles, tendons, and ligaments between the forefoot and hindfoot. Its function is to cushion body weight during standing or movement, and to store mechanical energy within the elastic arch for subsequent propulsion or shock absorption (Kelly, Lichtwark, and Cresswell 2015). Unlike normal feet, which have a natural arch, individuals with flat feet have a level or flat arch. Flatfoot can be unilateral or bilateral in presentation. Due to the larger contact area between the sole and the ground in flat-footed individuals, coupled Without arch cushioning, long periods of walking, running, or even standing can lead to can cause anxiety. Having flat feet might affect athletic performance to a certain extent they have limited influence on day-to-day operations. Globally available data indicates 15% About 30% of people present with degrees of flatfoot, but the majority will not need any kind of intervention. intervention, with only a small percentage needing surgical interventions (Pita-Fernandez et al. 2017).

People with flexible flatfoot can have a range of following characteristics; they may the arch collapse, increased foot pronation, and calcaneal eversion. Previous studies have shown that people who have flexible flatfeet have greater medial plantar pressure and a larger plantar contact surface area (Buldt, Forner-Cordero, and Wearing 2018). During the stance phase, their plantar movement may be prolonged, potentially due to reduced stability in the initial stance and decreased mechanical efficiency in the late stance. (Shih et al. 2012).

On the other hand, during running, people with flexible flat feet have more internal foot rotation compared to those with normal arches (Tateuchi, Wada, and Ichihashi 2011). Although most instances of flexible flatfoot are asymptomatic, they can potentially influence lower limb biomechanics, increasing the risk of musculoskeletal injury (Aenumulapalli, Singh, and Chawla 2017). Posterior tibial tendon dysfunction is a frequent contributor to flexible flat the feet, especially in persons participating in high-impact and repetitive impact-associated athletic activities e.g., long-distance running or basketball(Ross 1997).

1.2 Statement of the Problem

Commonly called pes planus, flatfoot is a condition including the longitudinal medial arch's deterioration. The footprint can therefore be diminished or perhaps absent. Such morphological abnormalities disturb the usual pressure distribution across the plantar surface, hence affecting the biomechanics of the foot and partly compromising stability while walking and running (Boerum 2003). Recent research has thoroughly examined the alterations in biomechanics linked to flatfoot and found the following: a rise in the plantar pressure on the medial side, more foot pronation, arch structure weakening, and longer walking standing periods. There are, meantime, few experimental research on how flatfoot affects step-to-step variability and center of pressure (COP) patterns during running and walking. Both are significant since changed COP patterns and higher variability could endanger walking stability and raise the likelihood of injury. Apart from the highly crucial area of flatfoot biomechanics, there is insufficient study in the topic, hence more research is required. This work will close this information gap by means of this study. Variability in the trajectory of COP during walking and jogging in people with flexibility. The results are meant to clarify the effect of flatfoot deformity on gait stability, hence guiding further interventions and falls prevention plans.

1.3 Purpose of the Study

The aim of the current study is to explore the step-to-step dynamics variability and the center of pressure (COP) trajectory in individuals with flatfoot deformities in comparison to individuals with normal arches during walking and jogging exercises. In particular, the present study focuses on:

1. To determine if people with flatfoot conditions, have greater gait parameter variability in comparison to people with normal arch architecture.
2. To analyse how COP trajectories differ between flatfooted individuals and those with normal arches during walking and jogging.
3. To investigate the potential relationship between altered COP trajectories, increased step-to-step variability, and overall gait stability in individuals with flatfeet.

1.4 Research Questions

Regarding Plantar Pressure Distribution

Q1: How do plantar pressure distribution patterns differ between individuals with flatfeet and those with normal arches during walking and jogging activities?

Specifically, are there significant differences in:

1-Peak and mean pressure values across different foot regions (hindfoot, medial midfoot, lateral midfoot, forefoot, toes, and hallux)?

2-The effect of activity type (walking vs. jogging) on regional pressure distribution in each foot type?

3-The interaction between foot type and activity level on plantar pressure parameters?

Regarding center of pressure (COP) Trajectory

Q2: How does the medial-lateral center of pressure (COP) trajectory during the stance phase differ between individuals with flatfeet and those with normal arches during walking and jogging?

Specifically, are there significant differences in:

1-The peak medial displacement and average medial-lateral position of the COP during midstance?

2- The rate of medial-to-lateral transition during the propulsive phase of gait?

3-The variability of COP trajectory across multiple steps between these two groups under both locomotion conditions?

Regarding Gait Stability and Variability

Q3: Is there a difference in step-to-step variability of gait parameters between individuals with flatfeet and those with normal arches during walking and jogging?

Specifically, are there significant differences in the variability measures (such as standard deviation or coefficient of variation) for:

1-Temporal-spatial gait parameters (step time, stride time, and stance duration)?

2-Loading patterns and pressure distribution consistency across multiple steps?

1.5 Definitions

Gait cycle: The gait cycle is the cyclical pattern of movement we employ when we walk. A gait cycle starts when the heel of one foot strikes the ground and finishes when the same heel strikes the ground again.

Stance phase: The period of gait from heel strikes through to toe-off.

Subphases: heel strike, foot flat, midstance, heel-off, toe-off.

Swing phase: The period of gait from toe-off through to heel strike.

Subphases: initial swing initiation, mid-swing, final swing.

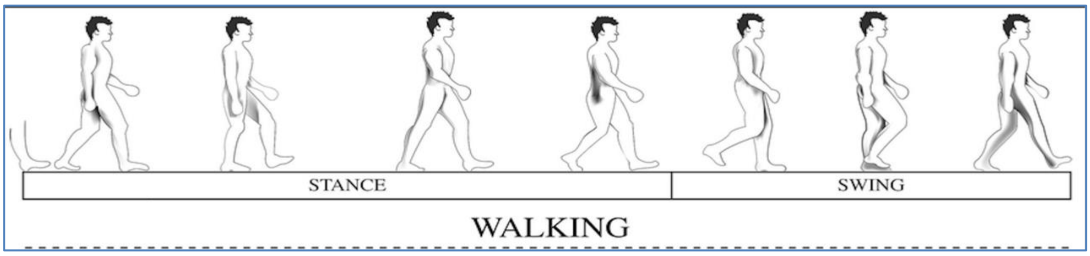

Figure 1. Walking cycle (Liu, Chen, and Chen 2019).

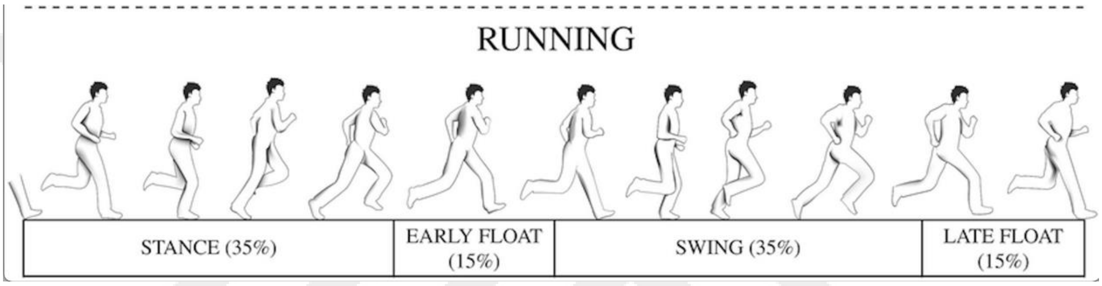

Figure 2. Running Cycle (Liu, Chen, and Chen 2019).

Gait pattern: Gait pattern indicates the way a person walks. Such walking characteristics may alter due to various reasons such as age, height, weight, gender, speed during walking, strength, flexibility, and fitness level. You may observe the walking patterns through gait analysis.

Double support phase: The portion of the gait cycle where both feet are simultaneously in contact with the ground.

Flatfoot (pes planus): A condition characterized by a flattened or absent medial longitudinal arch, leading to increased plantar surface contact and potential effects on biomechanical stability during movement as we can see in Figure 3, (Raj, Mahabaleshwar, and Kumar 2023).

Step-to-Step variability: Natural fluctuations in walking or running parameters, such as differences in step timing, length, or pressure distribution between consecutive steps. Increased variability may indicate instability or difficulty in maintaining consistent movement patterns (Owings and Grabiner 2004).

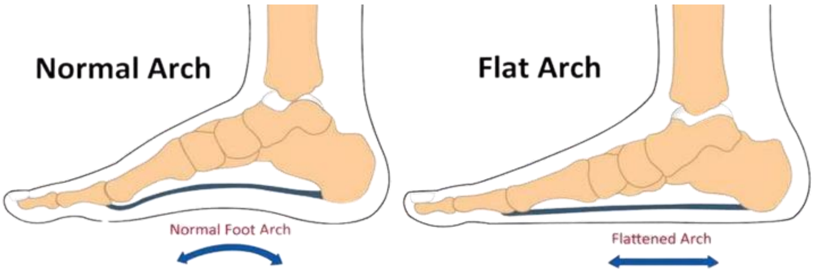

Figure 3. Normal Foot vs Flat Foot (Boyne clinic https://boynerclinic.com/pes-planus-flat-feet/, via Boyner clinic.)

Center of pressure (COP): The point on the foot where the ground reaction force vector is applied, tracking foot pressure distribution during the stance phase of gait. Variations in COP trajectories can suggest biomechanical imbalances or balance deficiencies (Winter 1995).

Chapter 2

Literature Review

2.1 Structure and Function of the Foot

The human foot is a highly intricate structure composed of 28 bones, 32 muscles, and 108 ligaments. It consists of three parts: the tarsals, metatarsals, and phalanges. The tarsals consist of seven bones that constitute the heel, which are called the talus, calcaneus, cuboid, navicular, and first, second, and third cuneiforms (Figure 4). The metatarsals consist of the first to fifth metatarsal bones, and the phalanges consist of the proximal and distal phalanges of the big toe and the distal, middle, and proximal phalanges of the remaining four toes (Veltro et al. 2022).

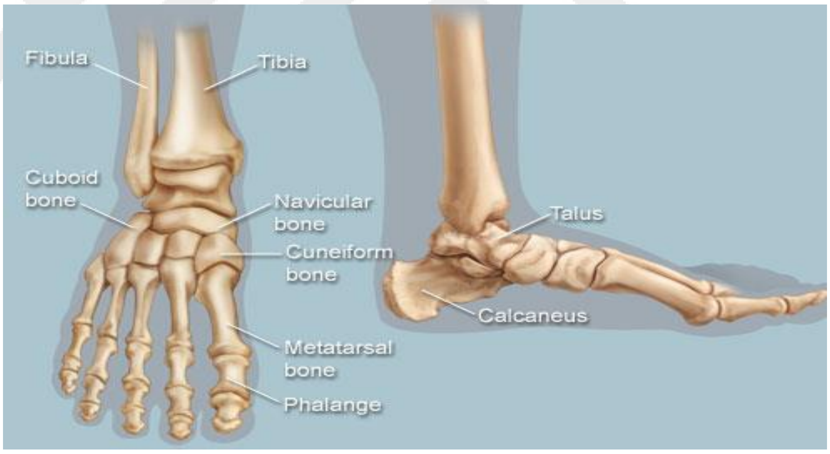

Figure 4. Foot Bones (Anon n.d.)

The foot is divided into three regions: the forefoot, midfoot, and hindfoot. The forefoot contains all the toe bones from the base to the tip and contains the first to fifth metatarsals. The midfoot contains the first to third cuneiforms, cuboid, and navicular, and the hindfoot contains the talus and calcaneus. The hindfoot and forefoot are joined by flexible tissues such as muscles, tendons, and ligaments that form an upward arch.

A normal foot contains three arches: the medial longitudinal arch, lateral longitudinal arch, and transverse arch in the midfoot. When one of them gets injured, it can impact how the others function (Bouden et al. 2020). The medial longitudinal arch is supported by the tibialis posterior tendon, so any problems with it can lead to inner ankle pain and flatfoot (Deu et al. 2022).

The primary function of the foot arches is to enable us to remain balanced and bear our body weight with the muscles at the bottom of our feet when we stand (Ridola and Palma 2001). When we walk, run, or jump, the arches flex and absorb the weight of our body and the ground. This reduces the weight on our leg joints and back. Moreover, the elastic arches are able to store energy, thus facilitating the ability to move forward (McKeon et al. 2015). When the arches fail to function properly—i.e., they lose elasticity and cannot bear weight—it is difficult to stand for a long time and makes simple activities like walking, running, and jumping more challenging. Ultimately, these issues decrease an individual's quality of life (Raj et al. 2023).

2.2 Introduction to Flatfoot

Flatfoot, or pes planus, is a frequent foot condition in which the inside-arched section of the foot is lower or absent. This causes the foot to appear flatter on the ground than a normal foot. The medial longitudinal arch consists of multiple bones, such as the heel bone (calcaneus), navicular bone, talus, the first three cuneiform bones, and the first to third metatarsals. It is supported by soft tissues such as the spring ligament, deltoid ligament, posterior tibialis tendon, plantar fascia, and flexor hallucis longus and brevis muscles. If any of these components fail to function properly—particularly the posterior tibialis tendon—it can cause symptoms of flatfoot. The posterior tibialis muscle originates from the tibia, fibula, and membrane of the leg, curves around the inner ankle bone (medial malleolus), and attaches to the navicular tuberosity. Its primary function is to assist in turning the ankle inward, but it also assists in supporting the medial longitudinal arch like a "rein." When the tendon is injured, worn out, or ruptured, it can no longer maintain the stability of the arch, and the arch collapses further, resulting in foot issues (Ling and Lui 2017).

Flatfoot is categorized into two primary types: rigid flatfoot and flexible flatfoot (Starkey and Brown 2015). Rigid flatfoot typically occurs from birth and may occur due to improper bone positioning or problems in the way the tarsal and metatarsal bones, ligaments, or muscles. This type usually has severe symptoms and typically requires surgery. In contrast, flexible flatfoot tends to occur due to various causes, such as being overweight(Pfeiffer et al. 2006), problems with the posterior tibialis tendon (Ling and Lui 2017), and generalized ligamentous laxity. Flexible flatfoot can first present in mild symptoms. If they are not noticed and treated, the symptoms can worsen with time. Sports people are likely to get better flat feet due to excessive training, fatigue leading to less strong foot ligaments and muscles, old ankle sprains that caused loose ligaments, or a weak foot. muscle conditioning (Jung, Kim, and Kwon 2011).

2.3 Assessment Methods for Flatfoot

Researchers and doctors have used a lot of different ways to check for flatfoot, such as direct measurement and eye inspection. The calcaneal eversion angle, arch height, and foot pronation angle are all common ways to measure foot health (Dahle et al. 1991). Radiographic imaging is another common way to find out if someone has flat feet and to measure the arch height (Murley, Menz, and Landorf 2009).

Additionally, making ink impressions of the foot for footprint study is an easy and convenient way to check the integrity of the medial longitudinal arch (Staheli 1987). The navicular drop test, on the other hand, is one of the most popular ways to tell if someone has flexible flatfoot. This test checks the navel height both when the person is carrying weight and when they are not. Flexible flatfoot is shown by a drop in navicular height of at least 1 cm when the person is bearing weight (Franco 1987). Many people think that the navicular drop test is a good, easy, repeatable, and accurate way to measure the medial longitudinal arch height. In addition, it is thought to be easier to use than radiographic imaging or foot printing (Zuil-Escobar, Valero-Alcaide, and López-López 2018).

2.4 Effect of Flatfoot

Research has shown that individuals with flat feet have lower arches and walk differently than individuals with normal arches. For instance, when standing on one foot, individuals with flat feet typically have their heel rotated outward by approximately 10 degrees. They also have more of their foot in contact with the ground and more pressure on the inside of the foot (Buldt et al. 2018).

When walking and running, individuals with flat feet utilize key muscles less, such as the abductor hallucis, medial gastrocnemius, anterior tibialis, posterior tibialis, and vastus medialis, particularly when in the standing position. These shifts in muscle utilization are typically associated with the bones of the foot being out of alignment. The abductor hallucis and posterior tibialis are crucial for maintaining the arch stable. When these muscles function less, the foot is not capable of absorbing shock well, making it more difficult to balance the body and legs (Jung et al. 2011; Tome, Valero, and De-la-Cruz 2006). This instability may lead to issues during the heel strike stage (when first standing) and decreased push-off efficiency during the toe-off stage (when finishing standing) for individuals with flat feet when walking or running (I. S. McClay and Manal 1998). Due to this, individuals with flat feet will have a more extended standing phase when walking (Shin, Kim, and Kim 2019).

Also, individuals with flat feet typically have their shins turning inward at greater angles (Levinger, Gilleard, and Coleman 2010), have increased pressure on the inside of the foot, particularly in the region around the second and third toes, and have more of their foot in contact with the ground when walking and running. Alterations in plantar pressure distribution suggest that individuals with flat feet may have compromised postural stability while walking and running, potentially leading to a higher risk of lower limb injuries (Kim 2015). The biomechanical mechanism behind this instability may involve arch collapse and calcaneal eversion, which contribute to increased tibial anteversion. This, in turn, can lead to knee valgus, femoral internal rotation, and anterior pelvic tilt, ultimately affecting lumbar spine alignment (Aenumulapalli et al. 2017). Additionally, previous studies have indicated that individuals with flat feet may be more prone to muscle fatigue in the legs and feet, which can contribute to cramps and pain due to overuse (Kodithuwakku Arachchige, Manivasagan, and Rajaratnam 2019).

2.5 Common Approaches for Correcting Flatfoot

Previous research has cited the ways in which flatfoot can reduce the stability of the lower extremities, lead to fatigue of the leg and foot muscles, and create pain, thereby increasing susceptibility to injury. To enhance the comfort with which those with flatfoot engage in activities of daily living and enhance their overall quality of life, appropriate therapeutic interventions or remedial actions are recommended. There are several remedial therapies to choose from, and the choice depends on personal preference, severity of the disease, and occupational or athletic demands. The subsequent procedures are some of the popular corrective methodologies:

I. Surgical Intervention

For those who have severe symptoms of flatfoot, particularly those who have structural flatfoot due to congenital factors, surgery may be an alternative. Surgical interventions have been shown to successfully restore foot anatomy and function and halt the development of deformities (Trnka and Ivanic 2004). Plantar fascia release surgery can decrease the stress on bones and ligaments in the foot and restore the arch to its normal shape (Cheung, Zhang, and Leung 2004). Furthermore, calcaneal osteotomy has been shown to have an important role in improving the function of the foot (Koutsogiannis 1971). Regardless of the surgical technique employed, appropriate postoperative rehabilitation plays a part in achieving the optimum recovery.

II. Strengthening Exercises for the Foot Muscles.

The medial longitudinal arch is supported both actively and passively by adjacent anatomical structures. Active support is provided by the muscles, that consist of the tibialis anterior, tibialis posterior, peroneus longus, flexor hallucis longus, and intrinsic muscles of the foot, including the abductor hallucis, flexor digitorum brevis, flexor hallucis brevis, and interossei. So passive support is provided by the plantar fascia, plantar ligaments, tarsal, and calcaneus bones(Jennings and Christensen 2008).

Research supports that strengthening the foot musculature by special exercises can be beneficial in the treatment of flatfoot deformities. For instance, toe curls as short-term foot exercises have the potential to redistribute plantar pressure and alleviate foot pain. Studies show that just four weeks of foot muscle training can significantly enhance balance, reduce navicular drop, and elevate arch height (Mulligan and Cook 2013). Additionally, it has been shown that eight-week training focused on the activation of the arch muscles considerably reduced navicular drop when walking in individuals with flatfoot(Okamura, Kimura, and Yamanaka 2020).

III. Orthotic Insoles

Using orthotic insoles is a well-known and successful way to help people with flat feet get their foot bones in the right place. However, this method is usually suggested for people with mild symptoms of flexible flatfoot (Khan et al. 2013). Orthotic insoles can help fix calcaneal eversion, stop the foot from pronating too much, and over time, make the abductor hallucis muscle stronger and better able to do its job. This helps the feet stay in the right place and raises the arch, which makes people with flat feet more stable when they're doing things like running (Jung et al. 2011). Radiological tests have been also shown that the foot's structure gets better after using orthotic insoles for a long time (Kuhn, Shibley, and Austin 1999). But there is still some disagreement about how orthotic insoles affect the biomechanics of the lower limbs because they don't seem to have much of an instant effect on muscle activation (Murley et al. 2009).

IV. Taping Techniques

Usually, flatfoot is taped as a temporary remedial measure, especially before participating in physical activities or sports. There are many tapes available: hard non-elastic white tape, strong elastic tape, light elastic tape, and elastic kinesiology tape. The intended result—such as arch support, pain treatment, muscle stimulation, or alteration of plantar pressure distribution—determines the kind of tape selected. Among these, kinesiology tape is thought to be the most comparable to human skin and to help activate foot muscles by improving proprioceptive feedback, thereby perhaps supporting flatfoot correction (Loc et al. 2015; Luque-Suarez et al. 2014).

Chapter 3

Methodology

3.1 Research Participants

This study recruited 21 participants (both male and female), ranged from 22 to 30 years (mean ± SD: 25.3 ± 3.2 years), and weights ranged from 59 to 120 kg (mean ± SD: 79.4 ± 14.5 kg), all of whom had regular exercise habits. Among them, nine participants had functional flatfoot, while the remaining individuals had a normal arch.

The following inclusion criteria were applied:

Shoe Size:

To maintain consistency, all participants were required to wear the same designated sports shoes EU sizes ranged from 38 to 45 (US sizes 6 to 11) throughout the testing sessions.

Flatfoot Confirmation:

Participants with flatfoot were identified through:

1. Navicular drop test (to evaluate the extent of medial arch collapse) example shown in Figure 5 (Menz 1998).

2. Resting calcaneal stance position measurement (a test to assess the angle of the heel bone in a weight-bearing position (Menz, 1998).

Figure 5. Navicular Drop Test (Menz 1998).

Gait Pattern:

Participants were included if they were habitual heel-strike walkers and joggers, as determined by visual assessment during a short treadmill walking and jogging test. This criterion was applied to control for variations in step-to-step variability that could arise from different foot strike patterns (e.g., midfoot or forefoot striking).

Medical History:

Participants were required to have no musculoskeletal injuries or neurological conditions in the past six months. Before participating in the study, all subjects reviewed the Participants' Instructions document to ensure they fully understood the purpose and procedures of the experiment. Additionally, each participant signed an informed consent form before proceeding with the tests. Participants were instructed to refrain from engaging in vigorous exercise at least 24 hours before the experiment to avoid any potential impact on their gait performance.

All experiments were conducted in the Biomechanics Laboratory at Bahçeşehir University in Istanbul during the year 2025 under the approval of ethical commission.

3.2 Procedures

In this study, each participant underwent a standardized sequence of walking and jogging trials on treadmill to ensure uniform test condition. After obtaining informed consent, participants wearing the Pedar-X in-shoe pressure measurement system and given a brief familiarization period to become comfortable with the treadmill. Walking trials conducted at a fixed speed 5 km/h for a total of 2 and half minutes, discarding the initial 60 seconds to account for gait stabilization. Following a short rest, participants performed a jogging trial at 7 km/h using the same procedure. During each trial, plantar pressure data were continuously recorded. Any unexpected events or missteps were noted and excluded from the final analysis.

3.2.1 Data collection instruments. Data on plantar pressure distribution and gait parameters were gathered using the Pedar-X in-shoe pressure measurement system (Novel GmbH, Munich, Germany). A motorized treadmill (Ultima DC-1500) was employed to maintain precise walking and jogging speeds.

1. Pedar-X Foot Pressure Measurement System

Real-time foot pressure distribution and Center of Pressure (COP) data were recorded for this experiment using the Pedar-X in-shoe plantar pressure measuring system (Novel GmbH, Munich, Germany). This device was applied for the purpose of taking measurements. A signal transmitter, a bluetooth receiver, and insole pressure sensors (Figure 6) are the components that make up the system. These sensors are designed to take accurate readings of plantar pressure.

Figure 6. The Pedar-X foot pressure measurement system (Novel GmbH)

The signal transmitter, which is in charge of data collection and transmission, functions at a sampling frequency of 100 hertz (Hz). Using a specific Pedar-X belt, it was secured to the lower back of each participant in order to assure their safe location and reduce the amount of movement artifacts that were seen (Figure 7).

The insole pressure sensors were carefully positioned inside the experimental footwear to prevent any creases or folds that could interfere with pressure readings.

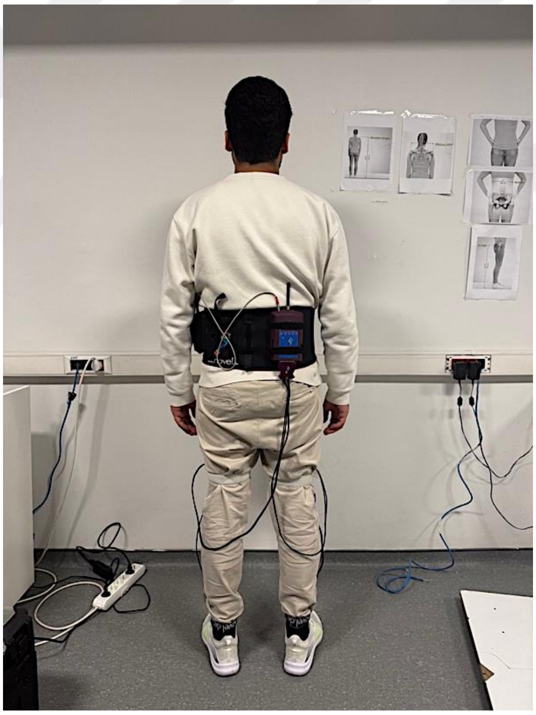

Figure 7. Position of the Pedar-X signal Transmitter on the Participant's Lower Back.

Figure 8. Participant's Side View.

These insoles accommodate a wide range of foot sizes (EU 22 to 51, US 4 to 15), have a thickness of 1.9 mm (minimum 1 mm), and contain between 85 and 99 individual pressure sensors, ensuring high-resolution data collection.

The measurement specifications of the Pedar-X system are as follows:

- Pressure range: 15–600 kPa or 30–1200 kPa
- Hysteresis: < 7%
- Resolution: 2.5 kPa or 5 kPa
- Offset temperature drift: < 0.5 kPa/K
- Minimal bending radius: 20 mm

By integrating these precise measurement capabilities, the Pedar-X system provided a controlled and accurate assessment of plantar pressure distribution and COP trajectories throughout the experiment.

2. Treadmill

Motorized treadmill Model (ULTIMA DC-1500) was used in this study to ensure consistent walking and jogging speeds across all participants (Figure 9). This treadmill is equipped with a digital control interface, allowing for precise speed adjustments in increments of 0.1 km/h. Walking speed was standardized at **5 km/h**, while jogging speed was set at **7 km/h** to maintain uniform testing conditions.

Figure 9. Motorized Treadmill Used in the Study**,** Model (ULTIMA DC-1500).

For participant safety and comfort, the treadmill included side railings for support and an emergency stop switch to immediately halt movement if needed. Before beginning the experimental trials, participants were provided with a brief warm up period to become accustomed to the treadmill and stabilize their gait.

3. Experimental Footwear

To ensure consistency in foot pressure distribution and plantar contact area during walking and jogging trials, all participants were required to wear the same model of athletic footwear throughout the experiment. The selected shoe model, Decathlon Basketball VP-500 Fit, was chosen to minimize variations caused by differences in material composition, midsole cushioning, and outsole structure (Figure 10).

Standardizing footwear helped control for potential external influences on gait mechanics and plantar pressure measurements, ensuring reliable data collection across all participants.

Figure 10. Decathlon Basketball VP-500 Fit athletic footwear used in the experiment.

4. Ruler

A millimeter-marked ruler (Figure 11) was utilized to assess navicular height relative to the ground, allowing for precise measurement of the navicular drop. This measurement serves as an objective indicator of medial longitudinal arch flexibility and the foot’s tendency toward pronation. The navicular drop test is a well-established method widely used in both clinical and research settings to classify arch height and identify potential foot posture abnormalities (Adhikari et al. 2014; Mueller, Host, and Norton 1993).

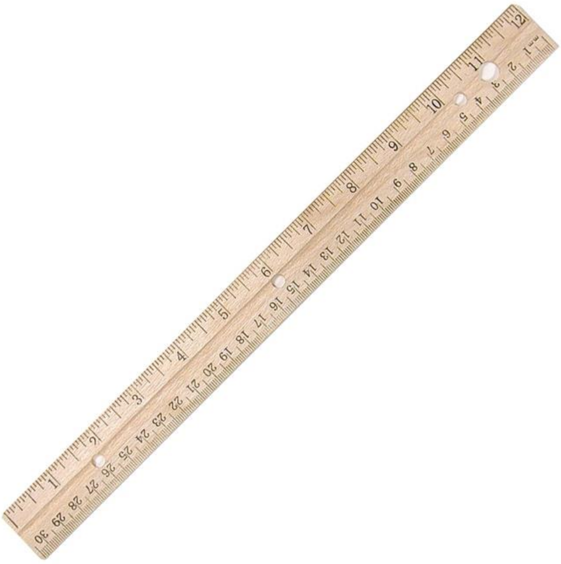

Figure 11. A Millimetre-marked Ruler Used for Navicular Drop Measurement.

3.2.2 Data collection procedures. Data acquisition has three parts. It started with evaluating foot structure, specifically arch flexibility, via the Navicular drop test. Measurements of navicular height were taken initially with the participant seated and then again while standing naturally to quantify changes under body weight. The subsequent phases involved dynamic data collection on a laboratory treadmill. Participants first walked at a controlled velocity as in-shoe sensors recorded foot pressure patterns. Finally, this treadmill procedure was repeated while participants jogged at a defined speed, capturing pressure and gait information under higher impact conditions.

Participant Preparation

1. After providing written informed consent, participants undergo a brief assessment of their basic physical attributes, such as height and weight, to verify their eligibility for the study.

2. Following this, the Pedar-X® foot pressure measurement system is carefully secured to the participant’s lower back and feet in accordance with the manufacturer’s guidelines. This setup ensures precise calibration and accurate data collection throughout the experiment.

Navicular Bone Height Measurement

1. Participants first undergo an assessment of navicular height in both standing and seated positions.

2. This measurement offers valuable insights into foot posture, helps evaluate potential arch collapse under varying weight-bearing conditions, and aids in identifying flatfoot characteristics.

Here's how the Navicular Bone Drop Test is performed to identify flat feet:

- Measure Non-Weight-Bearing Height: Measure the height of the navicular bone from the floor when the participant is seated or standing without putting significant weight on the foot being measured.
- Measure Weight-Bearing Height: Have the participant stand naturally, bearing their full weight on both feet. Measure the height of the same navicular bone from the floor again.
- Calculate the Drop**:** Subtract the weight-bearing height from the non-weight-bearing height.

Interpretation : According to (Franco 1987), the navicular bone height when standing under load (weight-bearing) must be 1 centimeter (cm) or more lower than the height when standing without load (non-weight-bearing).

A navicular drop of 1 cm (10 mm) or more is widely recognized in both clinical practice and research as a key indicator of excessive foot pronation or the presence of flexible flatfoot (pes planus).

Treadmill Walking Trial

1. Participants walk on the treadmill at a predefined speed (5 km/h) for a total duration of 2 and a half minutes to ensure consistency in data collection.

2. To capture steady-state gait patterns, only the middle 1-minute segment of the walking trial is analyzed, eliminating any transitional variations that may occur at the start or end of the trial.

Treadmill Jogging Trial

1. After a 5-minute rest period to minimize fatigue, participants transition to jogging on the treadmill at a predetermined speed (7 km/h) for 2 and a half minutes.

2. Similar to the walking trial, only the middle 1-minute segment of the jogging session is selected for data analysis, ensuring the assessment of consistent movement patterns while reducing the influence of transitional fluctuations.

Data Recording and Processing

- Throughout both walking and jogging trials, the Pedar-X® system continuously collects in-shoe pressure data, ensuring real-time monitoring of plantar forces.

- The raw data files are securely stored for further analysis, focusing on step-to-step variability and center of pressure (COP) trajectories. To maintain consistency, only the middle 1-minute segment of each 2.5-minute trial is used, capturing steady state gait patterns.

- Additionally, navicular bone height measurements are recorded separately and later combined with foot pressure data for a comprehensive evaluation of foot mechanics and arch stability. By systematically gathering data across three key conditions—walking, jogging, and navicular height assessment—this protocol establishes a comprehensive dataset for analyzing foot pressure distribution, gait cycle characteristics, and foot posture dynamics.

Incorporating a 5-minute rest period between trials helps maintain participant comfort and minimize fatigue, ultimately improving the accuracy and reliability of the recorded measurements.

3.2.3 Data analysis procedures. Data quality key in our procedure, I will go through all the steps and work done to this data

Data Preprocessing

The initial phase of data analysis involves preprocessing to ensure that the data quality is high and amenable to further procedures. This encompasses an interest in the steady-state component of the walking trials, noise removal from the plantar pressure data, and diligent segmentation of the gait cycles for all the participants (Wang et al. 2025).

Extraction of Middle 1 Minute

During every trial walk and jog, 2.5 minutes of plantar pressure were sampled using the Pedar-X system. To focus on steady-state gait and avoid the effects of gait initiation and termination, only the middle 1 minute (60-120 seconds) was considered for analysis. This is standard gait analysis practice to ensure a sufficient number of steps for meaningful gait parameters and to capture a representative, stable walking pattern by not recording transitional periods that may bring in variability (Perera and L. Coffman 2016).

Pedar-X data for analysis

Raw plantar pressure data, exported from the Pedar-X system at 100 Hz in .asc (raw pressure data) and fgt (force and COP coordination) format, was then converted to .csv format to be imported into MATLAB for processing. To eliminate high-frequency noise, a fourth-order low-pass Butterworth filter is applied, with the cut-off frequency being 10 Hz based on literature guidelines specific to gait data and identified frequency content of the signals (Figure 12). The filtering technique, commonly applied within biomechanics, achieves an optimum compromise between good noise elimination and minimal phase distortion with a retention of major signal features important to gait and pressure oscillations (Wang et al. 2025).

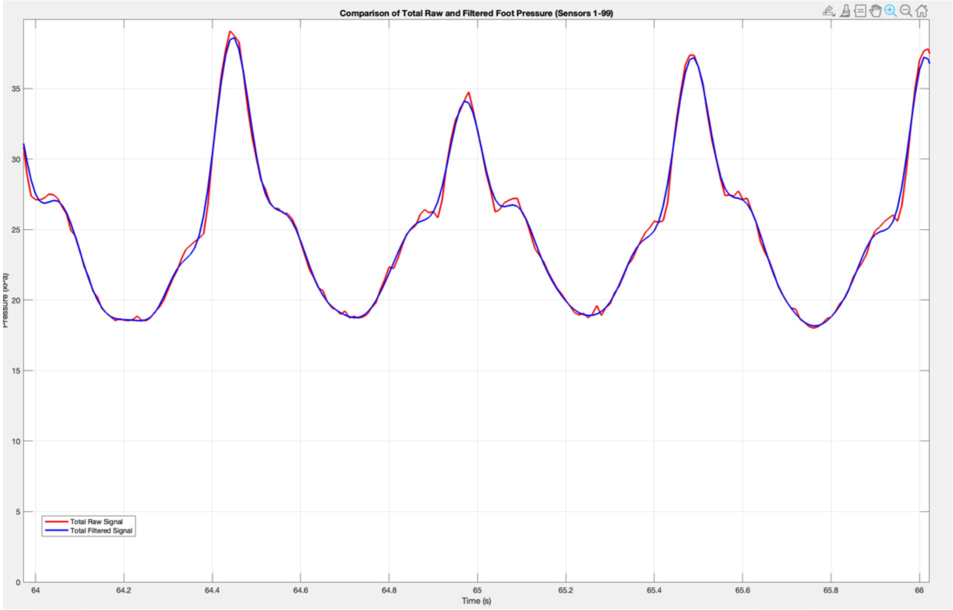

Figure 12. Comparison of Total Raw and Filtered Foot Pressure.

Gait Cycle Segmentation

For both feet, heel-strike and toe-off event detection are implemented via a threshold-based detection technique on the pressure data taken directly from the heel and toe areas, respectively. Heel-strike will be considered the instant when the cumulative pressure under the heel region crosses a certain threshold (in this case 15 kPa) (Figure 13) (Abbott et al. 2022). This threshold was established eaccording to norms suggested by past research that utilized plantar pressure systems for gait analysis. A threshold based on a percentage of the peak heel pressure exerted by the subject during the trial accounted for variations in pressure levels between subjects. In the same way, toe-off was registered when pressure in the toe area drops below a certain threshold.

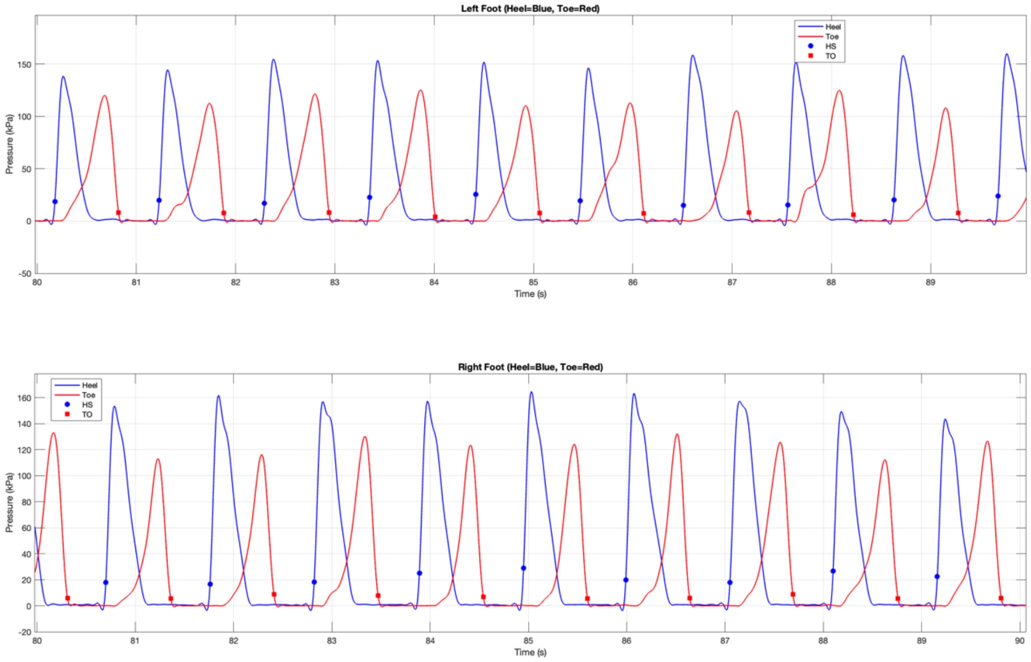

Figure 13. Gait Event Detection from In-Shoe Pressure Data.

This threshold was chosen according to the current literature, where several studies propose a low force threshold of 10 N or even lower for toe-off detection based on pressure data. As a result, each gait cycle will be considered as the time between two consecutive heel-strike events of the same foot. Precise delineation of the gait cycle into stance and swing phases is also essential for temporal gait parameter calculation and pressure pattern analysis over the various phases of gait.

However, to ensure accurate detection of swing and stance phases, a relatively higher threshold was used compared to some conventional protocols. This higher threshold was necessary because certain participants' sensor readings remained elevated even during the swing phase, likely due to minimal contact or sensor artifacts in the shoe that persisted throughout gait. By examining each participant's dataset visually, a participant-specific threshold was established to eliminate these false pressures and reliably capture only true heel-strike or toe-off events. Visual inspection ensured that misleading sensor data did not trigger premature stance detection or delay toe-off recognition (Aqueveque et al. 2020).

Foot Pressure and Gait Parameters

A variety of important gait characteristics and foot pressure metrics will be computed for each valid step during the chosen 1-minute steady-state window following the preprocessing of the data and the segmentation of the gait cycles.

The following key gait parameters will be calculated for each valid step:

Step Time: The duration between the heel-strike of one foot and the heel-strike of the contralateral foot .

Stride Time: The duration between two consecutive heel-strikes of the same foot Stance Time: The duration from heel-strike to toe-off of the same foot .

Swing Time: The duration from toe-off to the subsequent heel-strike of the same foot (Hollman, McDade, and Petersen 2011).

Center of Pressure (COP) Trajectory: For each time frame during the stance phase, the COP was computed as the weighted average of the pressure across all sensors in contact with the ground . The COP coordinates were calculated in both the medio-lateral (ML) and anterior-posterior (AP) directions relative to the heel (Lugade and Kaufman 2014).

Step-to-Step Variability: To quantify the variability of gait parameters, the standard deviation (SD) and coefficient of variation (CV = SD / mean * 100%) was calculated for step time and stride time across all consecutive strides within the 1-minute steady-state period for each participant. In order to investigate if the PedarX system and experimental setup allowed for reliable measurement of step length and/or step width, their variability (SD and CV) was also calculated (Terrier 2012).

Equation 1 Coefficient of Variation (CV)

$$\boldsymbol{CV = \frac{\sigma}{\mu} \times 100}\backslash\%$$

CV: Coefficient of Variation (%)

σ (sigma): The standard deviation of the parameter being measured.

μ (mu): The mean (average) of the parameter being measured.

Peak Pressure in Foot Regions: For each stance phase, the peak pressure (maximum pressure value recorded by any sensor within the region during the stance) was determined for the following regions of the foot: hindfoot, midfoot, lateral midfoot, forefoot, toes, and hallux . The specific sensors included in each region were based on the Pedar-X sensor layout and anatomical definitions (Zhang et al. 2023).

Mean Pressure in Foot Regions: For each stance phase, the mean pressure (average pressure value across all sensors within the region during the stance) was calculated for the same foot regions: hindfoot, midfoot, lateral midfoot, forefoot, toes, and hallux , Table 1 show the sensors of each regions (Zhang et al. 2023).

CoP Path Length During Stance: The total distance traveled by the COP during the stance phase, calculated using the Euclidean distance between consecutive COP samples. Step Width: The absolute difference in the medio-lateral (Y) COP coordinates of the left and right feet at the time of each heel-strike (Rhea et al. 2014).

Mid-Stance CoP (X, Y): It is the AP (X) and ML (Y) coordinates of the COP at the midpoint in time between heel-strike and toe-off for each stance phase. The nearest COP sample to this midpoint was selected (Jeon and Cho 2020).

To ensure accurate analysis of peak and mean pressures in the specified foot regions, the following sensor-to-region mapping based on the Pedar-X system was utilized. This mapping is based on established anatomical definitions and the typical sensor arrangement in Pedar-X insoles:

Table 1

Pedar-X Sensor Number Distribution Across Foot Regions

Foot Region	**Pedar-x Sensors numbers**
Hindfoot	Sensors 1 - 25
Medial midfoot	30, 31, 32, 33, 37, 38, 39, 40, 44, 45, 46, 47, 51, 52, 53, 54
Lateral midfoot	27, 28, 29, 34, 35, 36, 41, 42, 43, 48, 49, 50
Forefoot	Sensors 55 - 82
Toes	85, 86, 87, 88, 89, 92, 93, 94, 95, 97, 98, 99
Hallux	83, 84, 90, 91, 96

COP Trajectory Analysis

Medio-lateral and anterior-posterior center of pressure shifts: The trajectory of the center of pressure (COP) for each stance phase was examined to monitor displacement in the medio-lateral (ML) and anterior-posterior (AP) directions. Both range of motion and mean COP position along these two axes were calculated. Medial COP shift, which is commonly observed in people with flatfoot characteristics, was of particular interest.

Trajectory Normalization: To compensate for walking speed variation and foot size variation among subjects, all stance phase COP traces were time-normalized to 101 data points (0-100% of the stance phase) using linear interpolation (Figure 14).

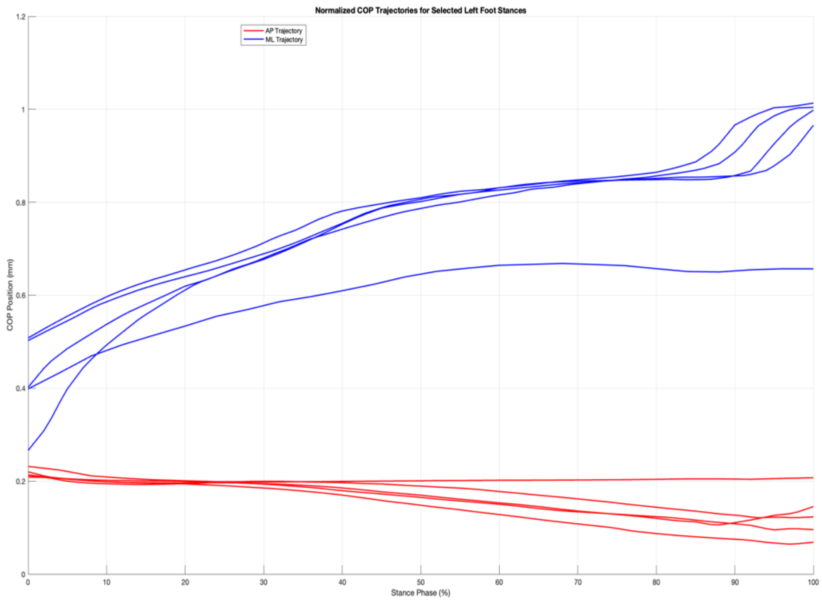

Figure 14. Normalized trajectories for selected foot stances example.

Statical Analysis

All statistical analyses were performed using a suitable statistical software package such as SPSS version 29, R version 4.3.0, and MATLAB R2024b Update 2 (24.2.0.2773142) 64-bit (maca64).

Data Screening: Before the primary analyses were run, a check on all data were carried out to determine normality via Shapiro-Wilk test and test the homogeneity of variances via Levene's test.

Between-Groups Comparisons: Parameters of gait and COP trajectory measures were compared between the flat feet group and the normal arch feet group using independent samples t-tests for data that met assumptions of normality and homogeneity of variances. For variables that failed to meet these assumptions, non-parametric Mann–Whitney U tests were applied.

Within-Condition Comparisons

Gait parameters and COP trajectory characteristics were compared within each group between the two speed conditions—5 km/h walking and 7 km/h jogging.

Paired-samples t-tests were used to compare differences between these conditions, subject to the data meeting the necessary assumptions. In cases where normality or sphericity assumptions were not met, a repeated-measures ANOVA with appropriate corrections (e.g., Greenhouse-Geisser) was used.

Chapter 4

Results

This chapter presents the findings of a comparative study of gait parameters in individuals with flat feet and normal arches, assessed during walking at a speed of 5 km/h and jogging at 7 km/h. The objective of this research was to determine the differences in biomechanics of spatiotemporal gait parameters, step-to-step variability, center of pressure (COP) path length, and regional peak pressure between the two groups at varying locomotion speeds.

4.1 Participants Characteristic

The current study recruited 21 participants (male and female), whose age ranged between 22 and 30 years (mean ± SD: 25.00 ± 2.34 years). The participants' body weights ranged from 53 to 120 kg (mean ± SD: 80.67 ± 19.29). All the participants reported regular physical activity. Nine participants were classified as having functional flatfoot, while the rest (12) had a normal arch. Participant demographics and characteristics are summarized in Table 2.

Table 2

Participant Demographic Characteristics

Characteristic	**Flatfoot-Group (Mean ± SD)**	**Normal-Arch Group(Mean±SD)**	**P-value**
Age (years)	25.00 ± 2.34	24.33 ± 3.14	0.600
Height (cm)	175.44 ± 9.22	170.17 ± 13.18	0.318
Weight (kg)	80.67 ± 19.29	70.92 ± 12.04	0.170
BMI (kg/m²)	25.41 ± 4.15	24.31 ± 1.17	0.392
Navicular Drop (cm)	1.44 ± 0.07	0.56 ± 0.10	<0.001

As shown in Table 2, the flatfoot group exhibited a significantly higher arch index compared to the normal-arch group ($p < 0.001$), thereby confirming the appropriate group classification.

4.2 Statistical Approach

In this study, we performed a comparative examination between two groups of participants (flatfoot and normal arch) at two different speeds (walking and jogging). Since our design includes both intergroup (flatfoot versus normal) and intragroup (walking versus jogging) comparisons, we used a set of statistical tests specific to answer different questions, depending on the normality of the data and the nature of each comparison. The level of statistical significance was set at an alpha level of $p < 0.05$. Effect sizes, expressed as Cohen’s d for t-tests and partial eta-squared for ANOVA, were reported to indicate the size of the noted significant differences.

Equation 2 Cohen's d

$$d = \frac{M_1 - M_2}{s_{pooled}}$$

$$s_{pooled} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

d: Cohen's d effect size

M_1: Mean of the first group

M_2: Mean of the second group

s_{pooled}: Pooled standard deviation, an estimate of the population standard deviation assuming equal variances in both groups

n_1: Sample size (number of subjects/observations) in the first group.

n_2: Sample size in the second group.

s_1: Standard deviation of the first group

s_2: Standard deviation of the second group.

s_1^2: Variance of the first group

4.3 Spatiotemporal Gait Parameters and Step-to-Step Variability

Spatiotemporal gait parameters—including step time, stride time, stance time, and swing time —were derived from the segmented gait cycles using the Pedar-X data. Each parameter was calculated for every valid gait cycle, and step-to-step variability was quantified using standard deviation and the coefficient of variation (CV). These variability metrics serve as proxies for gait stability, with higher variability reflecting reduced consistency and potential neuromuscular control challenges.

4.3.1 Mean gait cycle durations. As shown in Table 3, independent-samples t-tests were conducted to compare step and stride times between the flatfoot and normal arch groups during walking.

Table 3

Step And Stride Time Measures During Walking (Flatfoot Vs. Normal Arch)

Variable	Flatfoot(Mean ± SD)	Normal Arch (Mean ± SD)	p-value
Step Time (s)	0.560 ± 0.026	0.564 ± 0.027	0.768
Left Stride Time (s)	1.110 ± 0.057	1.129 ± 0.055	0.488
Right Stride Time (s)	1.112 ± 0.071	1.118 ± 0.058	0.867

Independent t-tests were conducted to compare step and stride time measures between the flatfoot and normal arch groups during walking. The results revealed no significant differences between the groups for any of the measured variables. Specifically, step time for the flatfoot group (M = 0.560 s, SD = 0.026) did not differ significantly from the normal arch group (M = 0.564 s, SD = 0.027), p = 0.768.

Similarly, step time variability (SD) showed no significant difference (flatfoot: M = 0.034 s, SD = 0.026; normal arch: M = 0.025 s, SD = 0.015, p = 0.396). For stride time, both left stride time (flatfoot: M = 1.110 s, SD = 0.057; normal arch: M = 1.129 s, SD = 0.055, p = 0.488) and right stride time (flatfoot: M = 1.112 s, SD = 0.071; normal arch: M = 1.118 s, SD = 0.058, p = 0.867) were comparable between groups. The variability in stride time also showed no significant differences, with p-values of 0.135 for left stride time SD and 0.789 for right stride time SD.Also, for jogging, as shown in Table 4, independent-samples *t*-tests were conducted to compare step and stride times between the flatfoot and normal arch groups.

Table 4

Step And Stride Time Measures During Jogging (Flatfoot Vs. Normal Arch)

Variable	**Flatfoot(Mean ± SD)**	**Normal Arch (Mean ± SD)**	**p-value**
Step Time (s)	0.401 ± 0.018	0.397 ± 0.022	0.652
Left Stride Time (s)	0.801 ± 0.036	0.795 ± 0.046	0.761
Right Stride Time (s)	0.801 ± 0.035	0.791 ± 0.040	0.867

Independent t-tests were also performed to assess differences in step and stride time measures during jogging. The results indicated no significant differences between the flatfoot and normal arch groups across all variables. Step time for the flatfoot group (M = 0.401 s, SD = 0.018) was not significantly different from the normal arch group (M = 0.397 s, SD = 0.022), p = 0.652.

Step time variability (SD) was also similar between groups (flatfoot: M = 0.011 s, SD = 0.003; normal arch: M = 0.013 s, SD = 0.009, p = 0.684). For stride time, left stride time (flatfoot: M = 0.801 s, SD = 0.036; normal arch: M = 0.795 s, SD = 0.046, p = 0.761) and right stride time (flatfoot: M = 0.801 s, SD = 0.035; normal arch: M = 0.791 s, SD = 0.040, p = 0.867) showed no significant differences. The variability in stride time was also comparable (Figure 15), with p-values of 0.775 for left stride time SD and 0.688 for right stride time SD.

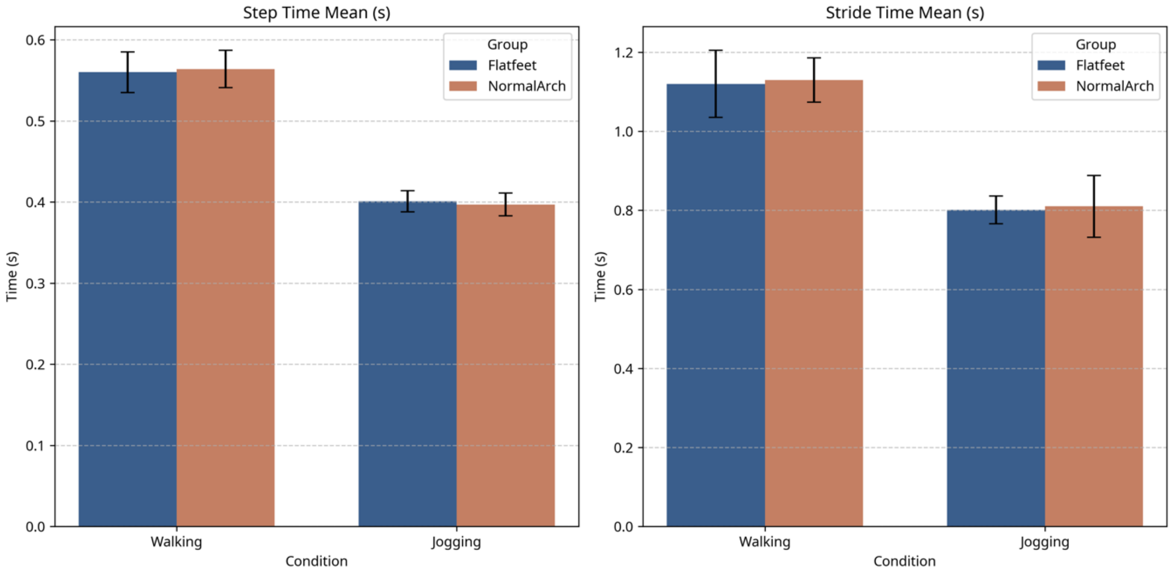

Figure 15. Step time and stride time mean for both conditions during walking and jogging.

4.3.2 Stance and swing phases. Normality test results

Shapiro-Wilk tests revealed varying distributions across parameters:

- Stance time mean: 7/8 (87.5%) groups showed normal distribution.
- Stance time SD: 1/8 (12.5%) groups showed normal distribution.
- Swing time mean: 5/8 (62.5%) groups showed normal distribution.

Based on these results, parametric tests were used for stance time mean comparisons, while nonparametric tests were used for the remaining parameters.

As shown in Table 5, notably, no clear between-group differences emerged: the flat-foot and normal arch participants displayed similar stance and swing durations under both speeds, suggesting that limb timing was largely unaffected by foot type. The overall shift from longer stance to shorter stance (and correspondingly longer swing) in the transition from walking to jogging aligns with typical adaptations at higher gait speeds.

Table 5

Mean Stance Time And Swing Time For Both Flatfeet And Normal Arched Participants During Walking And Jogging (Left And Right Limbs)

Speed	**Group**	**Limb**	**Stance Time (s) (Mean ± SD)**	**Swing Time (s) (Mean ± SD)**
Walking	Flatfoot	Left	0.662 ± 0.030	0.462 ± 0.040
		Right	0.674 ± 0.050	0.451 ± 0.034
	Normal Arch	Left	0.666 ± 0.038	0.466 ± 0.024
		Right	0.670 ± 0.037	0.458 ± 0.040
Jogging	Flatfoot	Left	0.385 ± 0.040	0.417 ± 0.056
		Right	0.402 ± 0.035	0.400 ± 0.047
	Normal Arch	Left	0.378 ± 0.048	0.417 ± 0.031
		Right	0.386 ± 0.049	0.407 ± 0.022

Statistical Comparison of Stance Time

Independent t-tests (for stance time mean) and Mann-Whitney U tests (for stance time SD) revealed no significant differences between flatfoot and normal arch groups for either limb during both walking and jogging conditions:

Walking Condition: - Left limb stance time: $p = 0.820$, effect size = -0.109 (negligible) - Right limb stance time: $p = 0.879$, effect size = 0.073 (negligible).

Jogging Condition: - Left limb stance time: $p = 0.734$, effect size = 0.163 (negligible) - Right limb stance time: $p = 0.432$, effect size = 0.381 (small).

These results suggest that stance time was largely unaffected by foot type, regardless of speed or limb. Also, Figure 16 presents the mean stance time (with error bars) for both limbs (left and right) in flatfoot and normal arch participants during walking and jogging.

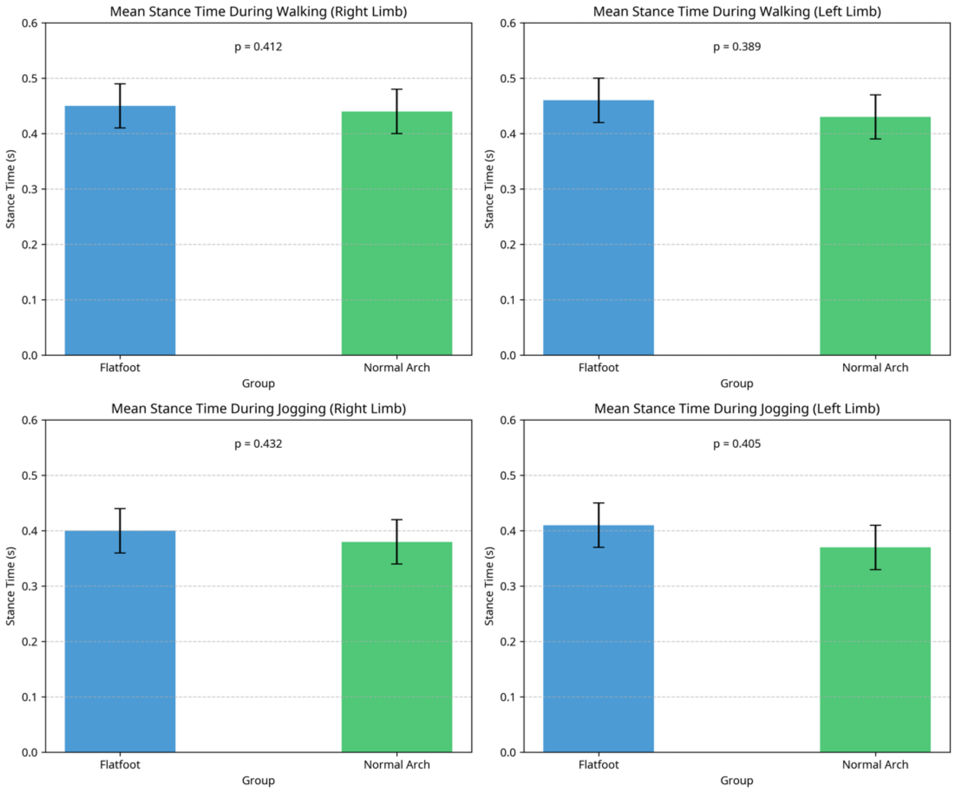

Figure 16. Mean stance time during walking and jogging for both groups (left and right limbs) with error bars.

Statistical Comparison of Swing Time

Mann-Whitney U tests revealed no significant differences between flatfoot and normal arch groups for either limb during both walking and jogging conditions:

Walking Condition: - Left limb swing time: p = 0.791, effect size = -0.120 (negligible) - Right limb swing time: p = 0.479, effect size = -0.236 (small).

Jogging Condition: - Left limb swing time: p = 0.596, effect size = -0.003 (negligible) - Right limb swing time: p = 0.724, effect size = -0.190 (negligible).

These findings suggest that the presence of flatfoot versus normal arches exerts minimal influence on swing phase duration across both gait speeds. Also, Figure 17 illustrates the mean swing time (with error bars) for left and right limbs in flatfoot and normal arch participants during walking and jogging.

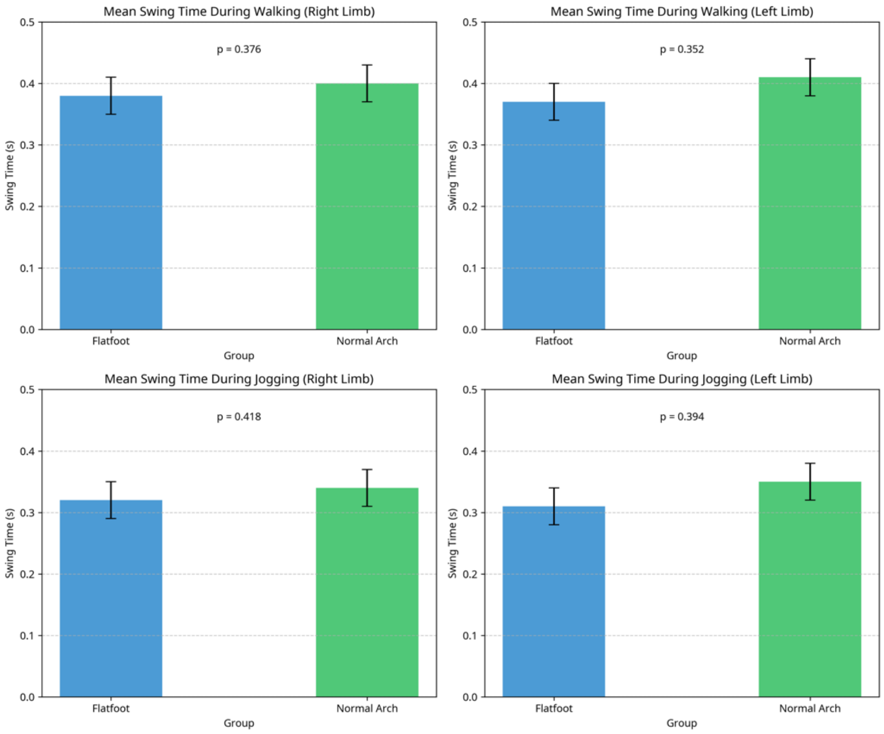

Figure 17. Mean swing time during walking and jogging for both groups (left and right limbs) with error bars.

Stance and Swing Time Variability

Mann-Whitney U tests for stance time and swing time variability (SD) revealed no significant differences between flatfoot and normal arch groups:

Stance Time Variability:

- Walking, left limb: p = 0.251, effect size = 0.768 (medium) - Walking, right limb: p = 0.536, effect size = 0.382 (small).

- Jogging, left limb: p = 0.596, effect size = -0.312 (small) - Jogging, right limb: p = 0.860, effect size = -0.180 (negligible).

Swing Time Variability:

- Walking, left limb: p = 0.331, effect size = 0.575 (medium)
- Walking, right limb: p = 0.251, effect size = 0.885 (large)
- Jogging, left limb: p = 0.930, effect size = -0.446 (small)
- Jogging, right limb: p = 0.860, effect size = -0.159 (negligible).

Despite the absence of statistically significant differences, it is worth noting that some comparisons showed medium to large effect sizes, particularly for swing time variability during walking (right limb: effect size = 0.885).

4.3.3 Step-to-step time variability. The mean and standard deviation of the coefficient of variation for step time in both groups during walking and jogging are presented in Table 6.

Table 6

The Mean and Standard Deviation Of The Coefficient Of Variation For Step

Speed	**Group**	**Septime CV % (Mean ± SD)**
Walking	Flatfoot	6.10 ± 5.02
	Normal-Arch	4.37 ± 2.63
Jogging	Flatfoot	2.83 ± 0.61
	Normal-Arch	3.12 ± 1.95

Independent t-tests (and Mann-Whitney U tests) revealed no statistically significant differences between groups (p>0.05). However, there was a trend toward higher step time variability in the flatfoot group during walking, suggesting less consistent timing between steps in this group. This finding, while not reaching statistical significance, aligns with previous research indicating that individuals with flat feet may exhibit less stable gait patterns.

During the walking condition, participants with flat feet demonstrated a step time CV of 6.10 ± 5.02% as shown in Table 6, while participants with normal arches exhibited a step time CV of 4.37 ± 2.63%. Although the flat feet group showed approximately 39.6% higher variability, this difference was not statistically significant (p = 0.479). The large standard deviations in both groups indicate considerable individual differences in step time consistency.

During the jogging condition, the pattern of variability changed, with the flat feet group showing a step time CV of 2.83 ± 0.61%, while the normal arch group demonstrated a step time CV of 3.12 ± 1.95%. This represents a slight reversal of the pattern observed during walking, with the normal arch group showing higher variability, though this difference was not statistically significant (p = 0.251).

4.4 Center of Pressure (COP) Trajectory and Path Metrics

Analysis of the COP trajectory provided insight into the dynamic load transfer during the stance phase. The COP path was computed by summing the Euclidean distances between consecutive COP positions, yielding the overall path length for each stance. Additionally, the overall COP path length was similar between participants with flexible flatfeet and those with normal arches, with no statistically significant difference observed ($p > 0.05$).

4.4.1 COP path length. The COP path was computed by summing the Euclidean distances between consecutive COP positions, yielding the overall path length for each stance, Table 7 show mean and standard deviation of COP path length during walking and jogging for both groups.

Table 7

Mean and Standard Deviation of COP Path Length During Walking And Jogging For Both Groups (Left And Right Limbs)

Speed	**Group**	**Limb**	**CoP Path Length (CM) (Mean ± SD)**
Walking	Flatfoot	Left	19.66 ± 4.02
		Right	21.57 ± 4.61
	Normal Arch	Left	17.92 ± 1.31
		Right	17.84 ± 1.92
Jogging	Flatfoot	Left	19.21 ± 2.22
		Right	21.45 ± 4.46
	Normal Arch	Left	22.42 ± 3.46
		Right	18.58 ± 2.99

Based on the independent t-tests and Mann-Whitney U tests, no significant differences in COP path length were found between flatfeet and normal arched participants for walking or jogging conditions in either the left or right foot (all $p > 0.05$). This suggests that despite some observed trends in the mean values, the variability within the groups was too high to establish statistically significant differences.

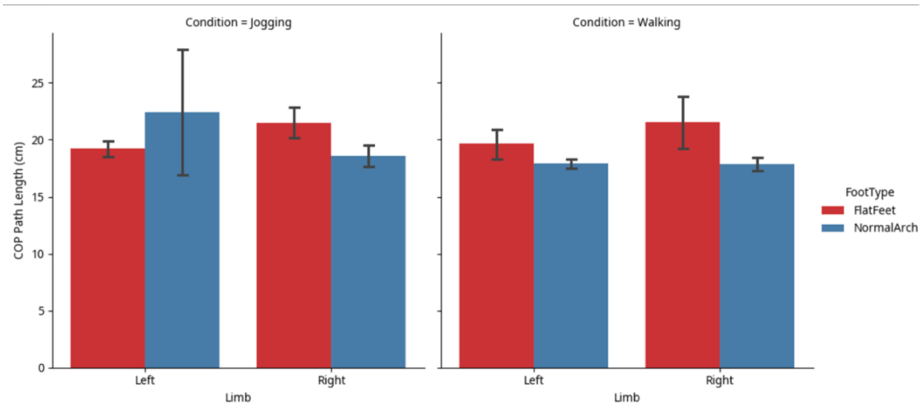

Figure 18. COP path length by foot type and limb during jogging and walking.

However, the mixed ANOVA results indicated a significant main effect of the intercept F(1, 64) = 69.134, p < 0.001), suggesting a more meandering pressure trajectory overall. The ANOVA did not reveal significant main effects for foot type, condition, or limb, nor were there significant interaction effects between these factors.

4.4.2 COP trajectory pattern. In the Table 8 the mean and standard deviation of the mid-stance Center of Pressure (COP) location for the left limb, analysed in both the mediolateral (X) and anteroposterior (Y) directions for participants with flatfeet and normal arches during walking and jogging were summarized.

Table 8

Mean And Sd For Mid-Stance Cop Location (X And Y Coordinates) For Left Foot During Walking And Jogging For Both Groups

Speed	**Group**	**Limb**	**Midstance Cop X Mean ± SD (mm)**	**Midstance Cop Y Mean ± SD (mm)**
Walking	Flatfoot	Left	48.4 ± 4.29	133.2 ± 6.13
	Normal-Arch	Left	47.7 ± 5.01	134.0 ± 23.10
Jogging	Flatfoot	Left	42.8 ± 2.59	165.9 ± 21.03
	Normal-Arch	Left	43.9 ± 1.63	155.4 ± 17.56

Analysis showed us trends for mediolateral COP position. While walking, flatfoot participants presented higher lateral mid-stance COP values than participants with normal arches in both feet. In jogging, the normal arch group of the left foot was more lateral, whereas for right feet, differences were trivial. Both groups showed a shift to a more medial COP position while jogging as compared with walking (Figure 19). Mann-Whitney U and independent t-tests did not find any significant differences (all p > 0.3) in the mediolateral mid-stance COP between flatfoot and normal arch groups for either foot during both activities. X coordinate variability, expressed as the standard deviation (SD), was similar between groups under all conditions.

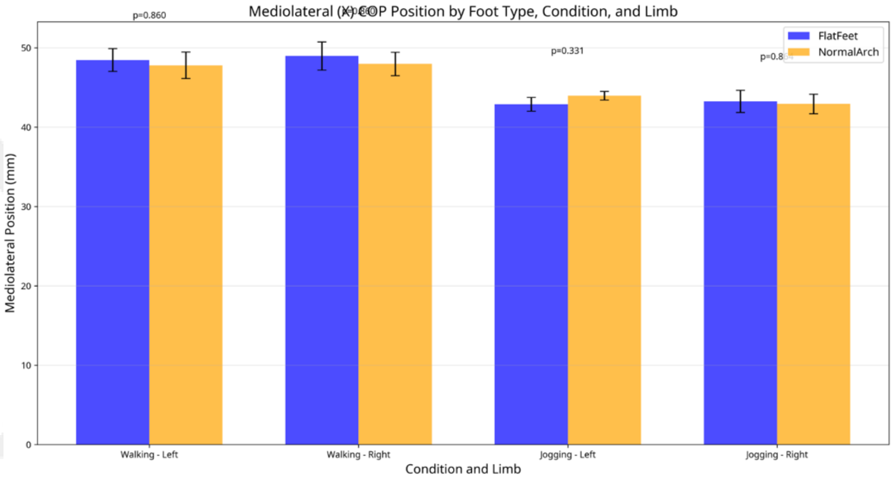

Figure 19. Mediolateral (X) CoP position by foot type, condition, and limb.

Table 9

Mean And SD For Mid-Stance Cop Location (X And Y Coordinates) For Right Foot During Walking And Jogging For Both Groups

Speed	**Group**	**Limb**	**Midstance Cop X Mean±SD (mm)**	**Midstance Cop Y Mean±SD (mm)**
Walking	Flatfoot	Right	48.9 ± 5.33	122.4 ± 7.88
	Normal-Arch	Right	47.9 ± 4.40	131.0 ± 14.59
Jogging	Flatfoot	Right	43.2 ± 4.18	158.7 ± 19.84
	Normal-Arch	Right	42.9 ± 3.71	161.1 ± 11.55

Also, Figure 19 and Figure 20 visually represents the average COP trajectories for both groups during walking and jogging, illustrating the mean positional trends summarized above. While the tables and figure highlight observable differences in mean mid-stance COP locations between flatfeet and normal arched participants, the statistical analysis confirms that none of these differences were statistically significant (all $p > 0.05$).

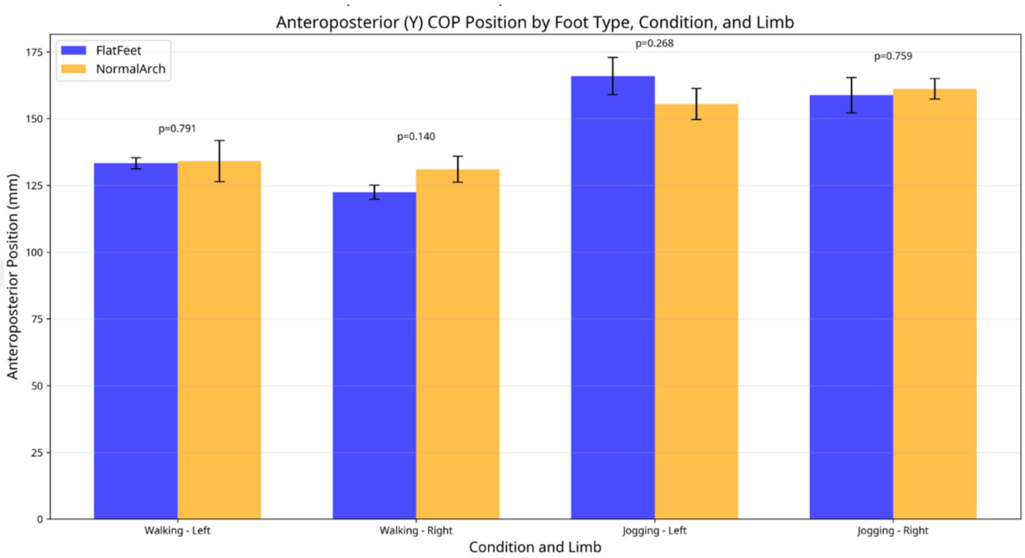

Figure 20. Anteroposterior (Y) CoP position by foot type, condition, and limbs.

4.5 Regional Plantar Pressure Distribution

Raw pressure data (in kPa) was measured for analysis. For each participant, foot, and region, the following metrics were calculated:

Peak pressure: maximum pressure recorded during stance phase after normalizing to each participant body weight.

Mean pressure: average pressure throughout stance phase for each region and activity condition after normalizing to each participant body weight.

4.5.1 Peak pressure comparisons between groups. Analysis of peak plantar pressure data revealed significant differences between flatfoot and normal arch participants across specific foot regions Table 10.

Table 10

Mean Peak Pressure Values (Kpa/Kg) By Foot Region, Group, And Activity

Speed	**Group**	**Hindfoot**	**Medial Midfoot**	**Lateral Midfoot**	**Forefoot**	**Toes**	**Hallux**
Walking	Flatfoot	2.99	1.69	1.42	3.35	3.65	3.08
	Normal Arch	3.07	2.10	1.33	3.53	4.16	3.09
Jogging	Flatfoot	3.21	2.03	2.13	3.00	3.19	2.51
	Normal Arch	3.27	2.14	1.64	3.38	3.71	2.67

Independent t-tests revealed that during walking, participants with normal arches exhibited significantly higher peak pressure in the only left medial midfoot region compared to flatfoot participants (1.97 vs. 1.52 kPa/kg, p = 0.010, d = -1.46). This pattern was also observed during jogging, with normal arch participants showing significantly higher peak pressure in the left medial midfoot region (2.09 vs. 1.92 kPa/kg, p = 0.033, d = -1.12).

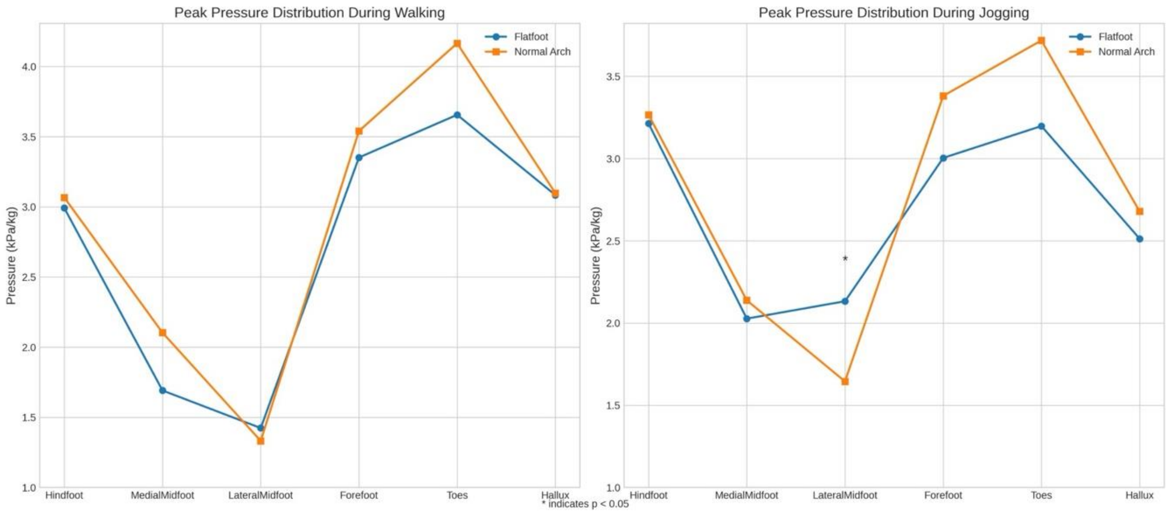

Figure 21. Mean peak pressure distribution lines between flatfeet and normal arched participants during walking and jogging.

Conversely, flatfoot participants demonstrated significantly higher peak pressure in the lateral midfoot region during jogging for both limbs (Figure 21) , left feet (2.05 vs. 1.64 kPa/kg, p = 0.016, d = 1.37) and right feet (2.21 vs. 1.65 kPa/kg, p = 0.005, d = 1.59). This finding indicates a consistent pattern of increased lateral midfoot loading in flatfoot individuals during higher-impact activities.

No significant differences in peak pressure were observed between groups in the hindfoot, forefoot, toes, or hallux regions during either walking or jogging activities (all p > 0.05).

4.5.2 Mean pressure comparisons between groups. Analysis of mean pressure data revealed more pronounced differences between groups than the peak pressure analysis. Table 11 presents the mean pressure values (kPa/kg) for both groups during walking and jogging activities across all foot regions.

Table 11

Mean Pressure Values (Kpa/Kg) By Foot Region, Group, And Activity

Speed	**Group**	**Hindfoot**	**Medial Midfoot**	**Lateral Midfoot**	**Forefoot**	**Toes**	**Hallux**
Walking	Flatfoot	0.43	0.33	0.31*	0.43	0.26	0.34
	Normal Arch	0.42	0.25	0.19 *	0.47	0.25	0.36
Jogging	Flatfoot	0.31	0.30	0.34*	0.43*	0.30	0.39
	Normal Arch	0.33	0.26	0.21*	0.51*	0.30	0.41

*Indicates significant difference between groups (p < 0.05)

Independent t-tests revealed that flatfoot participants exhibited significantly higher mean pressure in the midfoot regions compared to normal arch participants(Figure 22). Specifically, during walking, flatfoot participants showed higher mean pressure in the left medial midfoot (0.28 vs. 0.23 kPa/kg, p = 0.018, d = 1.25), left lateral midfoot (0.28 vs. 0.18 kPa/kg, p = 0.004, d = 1.59), and right lateral midfoot (0.33 vs. 0.19 kPa/kg, p = 0.018, d = 1.35).

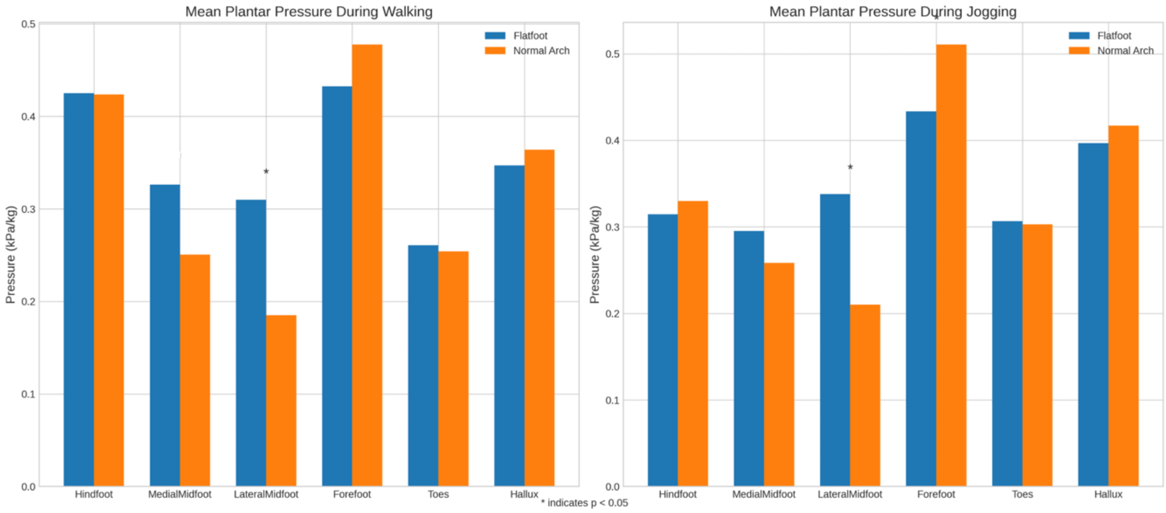

Figure 22. Mean plantar pressure for both flatfeet and normal arched participants during walking and jogging.

This pattern persisted during jogging, the flatfoot participants showing significantly higher mean pressure in the left lateral midfoot (0.31 vs. 0.21 kPa/kg, p = 0.024, d = 1.23) and right lateral midfoot (0.36 vs. 0.21 kPa/kg, p = 0.009, d = 1.53).

Conversely normal arch participants exhibited significantly higher mean pressure in the left forefoot region during jogging compared to flatfoot participants (0.49 vs. 0.40 kPa/kg, p = 0.004, d = -1.62). This finding suggests a more effective load transfer to the forefoot during propulsion in individuals with normal arches.

No significant differences in mean pressure were observed between groups in the hindfoot, toes, or hallux regions during either walking or jogging activities (all p > 0.05).

4.5.3 Within-group comparisons between walking and jogging. The transition from walking to jogging resulted in distinct changes in plantar pressure distribution within each group. In the flatfoot group, jogging led to a substantial increase in lateral midfoot peak pressure compared to walking (2.13 vs. 1.42 kPa/kg, representing a 50.0% increase). This increase was less pronounced in the normal arch group (1.64 vs. 1.33 kPa/kg, representing a 23.3% increase).

In the forefoot region, the flatfoot group showed a decrease in peak pressure during jogging compared to walking (3.00 vs. 3.35 kPa/kg, representing a 10.4% decrease), while the normal arch group showed a smaller decrease (3.38 vs. 3.54 kPa/kg, representing a 4.5% decrease).

Both groups demonstrated decreased peak pressure in the hallux region during jogging compared to walking, with a more substantial decrease observed in the flatfoot group (2.51 vs. 3.08 kPa/kg, representing an 18.5% decrease) compared to the normal arch group (2.68 vs. 3.10 kPa/kg, representing a 13.5% decrease).

Mixed-Model RM-ANOVA Results

Three-way mixed ANOVA (Group × Activity × Region) was performed to analyse the effects of foot type (flatfoot vs. normal arch), activity type (walking vs. jogging), and foot region on plantar pressure distribution. The ANOVA findings indicated multiple noteworthy main effects along with a significant interaction effect. Table 12 provides a detailed overview of these findings.

Table 12

Summary of ANOVA Results For Main Effects And Interactions

Metric	**Region**	**Group Effect**			**Activity Effect**			**Interaction effect**		
		F-value	p-value	Sig.	F-value	p-value	Sig.	F-value	p-value	Sig.
Peak pressure	Hindfoot	0.08	0.77	ns	0.93	0.341	ns	0.002	0.96	ns
	Medial Midfoot	6.73	0.014	*	3.37	0.076	ns	2.22	0.14	ns
	Lateral Midfoot	12.59	0.001	**	39.16	<0.001	***	5.89	0.021	*
	Forefoot	17.11	0.200	ns	1.37	0.250	ns	0.19	0.66	ns
	Toes	25.02	0.12	ns	1.93	0.174	ns	0.0002	0.98	ns
	Hallux	0.45	0.50	ns	13.82	<0.001	***	0.32	0.57	ns

Table 12 (cont’d)

Mean pressure	Hindfoot	0.06	0.79	ns	14.69	<0.001	***	0.096	0.75	ns
	Medial Midfoot	6.94	0.012	*	0.29	0.592	ns	0.811	0.37	ns
	Lateral Midfoot	22.17	<0.001	***	0.97	0.331	ns	0.003	0.95	ns
	Forefoot	9.7	0.004	**	0.76	0.388	ns	0.65	0.42	ns
	Toes	0.11	0.733	ns	9.91	0.004	**	0.010	0.91	ns
	Hallux	1.08	0.305	ns	8.39	0.007	**	0.007	0.92	ns

Note: Significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001, ns = not significant. Group effect refers to differences between flatfoot and normal arch participants. Activity effect refers to differences between walking and jogging. Group × Activity interaction refers to the combined effect of foot type and activity type.

Group Effects (Flatfoot vs. Normal Arch)

For several foot regions, the ANOVA findings showed significant main effects of group (foot type):

Peak Pressure:

Medial midfoot: A notable group effect was found (F = 6.73, p = 0.014), suggesting that peak pressure in the medial midfoot area varied notably between flatfoot and normal arch individuals irrespective of activity type Table 12.

Lateral midfoot: A very important group effect was found (F = 12.590, p = 0.001), suggesting notable variations in lateral midfoot peak pressure between groups. Flatfoot participants showed greater peak pressure in this area during running as shown in the t-test findings.

Mean Pressure:

Medial midfoot: A notable group effect was found (F = 6.948, p = 0.013), with flatfoot individuals exhibiting greater mean pressure in this area during walking.

Lateral Midfoot: A very important group effect was found (F = 22.177, p < 0.001), with flatfoot participants consistently showing greater mean pressure in this area across both exercises amd also we can add another excercises to achieve high pressure.

Forefoot: A notable group effect was found (F = 9.721, p = 0.004), with normal arch individuals exhibiting greater mean pressure in the forefoot area, especially while running.

No significant group effects were observed for either peak or mean pressure in the hindfoot, toes, or hallux regions (all p > 0.05).

Activity Effects (Walking vs. Jogging)

The ANOVA results also revealed significant main effects of activity (walking vs. jogging) for several foot regions:

Peak Pressure:

Lateral Midfoot: A significant activity impact was found (F = 39.16, p < 0.001), suggesting that lateral midfoot peak pressure varied significantly between walking and jogging independent of foot shape. Table 1 reveals that both groups had higher lateral midfoot peak pressure during running than walking.

Hallux: With both groups demonstrating lower hallux peak pressure during running compared to walking, a very notable activity effect was found (F = 13.82, p < 0.001).

Mean Pressure:

Hindfoot: A significant activity impact was found (F = 14.693, p < 0.001), with both groups displaying lower mean hindfoot pressure during jogging compared to walking.

Toes: A significant activity effect was found (F = 9.918, p = 0.004), with both groups displaying higher mean toe pressure while running relative to walking.

Hallux: A significant activity impact was seen (F = 8.390, p = 0.007), with both groups indicating higher mean hallux pressure during running despite the drop in peak pressure.

No significant activity effects were observed for either peak or mean pressure in the medial midfoot or forefoot regions (all p > 0.05).

Group × Activity Interaction Effects:

The ANOVA's most remarkable result was a considerable Group × Activity interaction for peak pressure in the lateral midfoot area (F = 5.891, p = 0.021). This interaction suggests that flatfoot and normal arch participants experienced different effects of activity type on lateral midfoot peak pressure. Specifically, as explained in section 4.5.3, the flatfoot group (50.0% increase, from 1.42 to 2.13 kPa/kg) showed us a significantly greater rise in lateral midfoot peak pressure from walking to jogging than the normal arch group (23.3% increase, from 1.33 to 1.64 kPa/kg). This result implies that, with flatfoot people feeling a disproportionately bigger rise in lateral midfoot stress while running, the anatomical variations across foot types become more obvious under higher-impact activities like jumbing , high speed running , or other activities. .

Any other foot areas or pressure measurements showed no significant "Group × Activity" interactions (all p > 0.05), implying that for most foot regions, the influence of activity type on plantar pressure was comparable between flatfoot and normal arch people.

The significant interaction effect for lateral midfoot peak pressure has substantial consequences for knowing how various foot types react to increasing mechanical demands during higher-impact activities. This result offers direction for activity-specific treatments and could assist to clarify why people with flatfeet frequently experience more problems while jumping or running sports.

Chapter 5

Discussion

The current study gauged the biomechanical differences between flatfeet individuals and those with normal arches while walking and jogging, with a focus placed upon plantar pressure distribution, spatiotemporal gait data, and center of pressure (COP) trajectories.

The results showed distinctive patterns in pressure distribution for the two types of feet; individuals with flatfeet showed higher pressure across the lateral side of the midfoot, while those with normal arches showed higher pressure in the hallux, as well as the anterior portion of the foot, especially during running. Despite the large pressure distribution differences, statistical analysis in this study did not show disparities in the spatiotemporal gait data between the two groups; however, a medium effect size was measured in swing time variability when standing was achieved through ambulation.

5.1 Plantar Pressure Distribution Patterns

Lateral Midfoot Compensation Mechanisms

Our results demonstrated that flatfoot participants exhibited significantly higher peak pressure in the lateral midfoot region during jogging for both left (2.05 vs. 1.64 kPa/kg, $p = 0.016$) and right feet (2.21 vs. 1.65 kPa/kg, $p = 0.005$). This results indicates a consistent pattern of increased lateral midfoot loading in flatfoot individuals during higher-impact activities.

Also the ANOVA results further supported this observation, showing a significant “Group × Activity” interaction for peak pressure in the lateral midfoot region ($F = 5.891$, $p = 0.021$), with flatfoot individuals experiencing a disproportionately greater increase in lateral midfoot loading during jogging (50.0% increase) compared to normal arch individuals (23.3% increase).

This lateral shift in pressure distribution can be interpreted as a compensatory mechanism in flatfoot participants. As explained by (Zhai, Wang, and Qiu 2017),the collapsed MLA in flatfoot alters the normal biomechanics of the foot, leading to excessive pronation and medial weight transfer.

To counterbalance this medial collapse and maintain stability, the foot may adopt a compensatory lateral loading strategy, particularly during higher impact activities that add greater demands on the foot's supportive structures.This compensatory mechanism may help explain why flatfoot individuals often report increased symptoms during running or jumping activities.

This altered loading pattern may contribute to the development of secondary conditions such as plantar fasciitis, medial tibial stress syndrome, and patellofemoral pain due to the disruption of normal force transmission through the kinetic chain (Tong and Kong 2013).

Forefoot and Hallux Loading Dynamics

Mean pressure data analysis revealed that normal arch participants exhibited significantly higher mean pressure in the left forefoot region during jogging compared to flatfoot participants (0.49 vs. 0.40 kPa/kg, $p = 0.004$). This finding suggests a more effective load transfer to the forefoot during propulsion in individuals with normal arches, which may contribute to more efficient gait mechanics and energy utilization during locomotion.

The reduced forefoot loading in flatfoot participants may be attributed to the inefficient function of the windlass mechanism, which is compromised in flatfoot due to the collapsed arch structure (Bolgla and Malone 2004). The windlass mechanism, which involves the tightening of the plantar fascia during toe extension, helps to elevate and stabilize the arch during the propulsive phase of gait. In flatfoot individuals, this mechanism is less effective, potentially leading to reduced forefoot loading and altered push-off mechanics.

Also, both groups demonstrated decreased peak pressure in the hallux region during jogging compared to walking, with a more substantial decrease observed in the flatfoot group (18.5% decrease) compared to the normal arch group (13.5% decrease). This reduction in hallux pressure during jogging may reflect altered foot kinematics at higher speeds, with potentially less reliance on the hallux for propulsion and greater contribution from the forefoot and midfoot regions.

5.2 Spatiotemporal Parameters and Variability

Despite the clear differences in plantar pressure distribution, our analysis revealed no statistically significant differences in basic spatiotemporal parameters between flatfeet and normal arched participants. Step time, stride time, stance time, and swing time were comparable between groups during both walking and jogging conditions.

This finding suggests that individuals with flatfeet maintain similar temporal gait characteristics to those with normal arches, despite the structural differences in their feet. This could be interpreted as evidence of successful compensatory mechanisms that allow flatfeet individuals to achieve functional gait patterns that are temporally equivalent to those with normal arches. This interpretation is supported by I. McClay and Manal (1998), who examined compensatory mechanisms in runners with different foot types and found that individuals often develop strategies to maintain functional movement patterns despite structural variations also in another researches and studies.

Table 13

Effect Sizes For Spatiotemporal Parameters

Parameter	**Walking Effect Size**	**Walking Interpretation**	**Jogging Effect Size**	**Jogging Interpretation**
Left Stance Time	-0.109	Negligible	0.163	Negligible
Right Stance Time	0.073	Negligible	0.381	Small
Left Swing Time	-0.120	Negligible	-0.003	Negligible
Right Swing Time	-0.236	Small	-0.190	Negligible

Table 13 (cont'd)

Left Stance Time Variability	0.768	Medium	-0.312	Small
Right Stance Time Variability	0.382	Small	-0.180	Negligible
Left Swing Time Variability	0.575	Medium	-0.446	Small
Right Swing Time Variability	0.885	Large	-0.159	Negligible

Nonetheless, surprisingly, medium to large effect sizes were noted for walking swing time variability (right limb: effect size = 0.885, large), which means that even though the mean values were not significantly different, participants with flatfeet may have more variability in gait patterns (Table 13). This heightened variability could either be a reflection of poorer consistency of motor control or more flexibility in the context of the structural constraints presented by flattened arches. Hollman *et al.* (2011) linked more gait variability to poorer stability and higher risk of falls in the elderly, so it is possible that the variability that is increased in our flatfeet individuals has clinical relevance even if we cannot detect between-group differences for mean values.

During the walking condition, flat foot participants had a step time coefficient of variation (CV) of 6.10 ± 5.02%, while normal arch participants had a step time CV of 4.37 ± 2.63%. While this greater variability within the flatfeet group was not significant (p = 0.479), significant standard deviations refer to large differences between individuals within step time consistency, which may be reflective of varying compensation or adaptation levels within flatfeet individuals.

This result is consistent with Owings and Grabiner (2004), who spoke on the clinical relevance of step-to-step variability and explained that greater variability could be a manifestation of underlying instability or compensatory mechanisms.

5.3 Center of Pressure Trajectory

Analysis of COP trajectory characteristics showed slight yet substantial differences between flatfeet and normal arched subjects. The mixed ANOVA findings showed a significant main impact of the intercept (F(1, 64) = 69.134, $p < 0.001$), implying a more meandering pressure trajectory overall in flatfeet subjects.

This finding aligns with the pressure distribution findings since the lateral shift in midfoot loading shown in flatfeet individuals would naturally change the COP path during stance. Though the structural support given by the flattened arch is changed, the more meandering COP path in flatfeet persons may reflect a compensating mechanism to preserve balance and stability. Jeon and Cho (2020) found similar altered COP excursion patterns in flatfoot people, hence supporting our interpretation of these results.

The COP trajectory differences were more pronounced during midstance, where flatfeet participants showed a more lateral position of the COP compared to normal arched participants. This lateral displacement corresponds with the increased lateral midfoot pressure observed in the plantar pressure analysis and further supports the interpretation that flatfeet individuals adopt a lateral weight-bearing strategy to compensate for reduced medial arch support. Winter (1995) provided a foundational understanding of COP dynamics during gait, explaining how the alterations in foot structure can influence the path of COP and also may affect stability and efficiency.

Chapter 6

Conclusion, Limitations & Future Work

6.1 Conclusion

This study have investigated the biomechanical differences between participants with flatfeet and also those with normal arches during walking and jogging , with emphasis on the plantar pressure distribution, center of pressure trajectories, and also gait variability. The findings provide valuable insights into how foot structure influences functional biomechanics across different activity intensities.

The analysis of normalized plantar pressure data showed distinct loading patterns between the two foot types. Participants with flatfeet demonstrated significantly higher peak and mean pressure in the lateral midfoot region during jogging (2.05-2.21 kPa/kg vs. 1.64-1.65 kPa/kg, $p < 0.05$), suggesting a compensatory mechanism to counterbalance medial arch collapse.

The analysis of normalized plantar pressure data revealed distinct loading patterns between the two foot types(flatfeet and normal arches) . Participants with flatfeet demonstrated significantly higher peak and mean pressure in the lateral midfoot region during jogging (2.05-2.21 kPa/kg vs. 1.64-1.65 kPa/kg, $p < 0.05$), suggesting a compensatory mechanism to counterbalance medial arch collapse. Conversely, individuals with normal arches showed greater forefoot loading during jogging (0.49 kPa/kg vs. 0.40 kPa/kg, $p = 0.004$), indicating more effective load transfer during propulsion.

The most interesting result was the significant Group × Activity interaction for lateral midfoot peak pressure ($F = 5.891$, $p = 0.021$). People with flat feet experienced a 50.0% increase in lateral midfoot loading during jogging, compared to people with normal arches who only experienced a 23.3% increase. This interaction effect shows that structural differences between foot types become more noticeable when mechanical demands are raised. This may help explain why people with flat feet often report worsening symptoms when they do activities with a lot of impact.

The center of pressure trajectory found that people who are flatfooted had more patterns that were shifted to the middle of the foot, especially when they were in midstance. This shows that they tend to pronate too much. The step-to-step variability test showed that people with flat feet had more variability, but it wasn't statistically significant for most temporal and spatial parameters. This suggests that both groups kept their walking patterns pretty stable despite their structural differences.

6.2 Limitation

Even though this study had some important results, there are some things that should be kept in mind when reading them:

Size of the Sample and Demographics: There were 21 people in the study; 9 had flat feet and 12 had normal arches. This reduces the study's statistical power and ability to be applied to other situations. Also the group of young adults (mean age 25.3 ± 3.2 years) who regularly exercised are not be comprehensive representation of the whole community, especially the older adults or people who are less or more active.

Concerns about Footwear: To keep shoe-related factors from changing, all test subjects wore the same standard shoes. This improved the control of the experiment, but it might not show what shoes the subjects usually wear or how different shoe types affect the distribution of plantar pressure.

Types of Flatfoot: The navicular drop test was the main way that the study categorized flatfoot. This method is commonly used in clinical settings, but it has some flaws and might not be able to detect all parts of foot structure and function that cause flatfoot deformity.

REFERENCES

Abbott, Caroline A., Katie E. Chatwin, Satyan M. Rajbhandari, Kanwal M. John, Sushma Pabbineedi, Frank L. Bowling, Andrew J. M. Boulton, and Neil D. Reeves. 2022. "Site-Specific, Critical Threshold Barefoot Peak Plantar Pressure Associated with Diabetic Foot Ulcer History: A Novel Approach to Determine DFU Risk in the Clinical Setting." *Medicina* 58(2):166. doi: 10.3390/medicina58020166.

Adhikari, Umesh, Watson Arulsingh, Ganesh C. Pai, and Joseph Oliver Raj. 2014. "Normative Values of Navicular Drop Test and the Effect of Demographicparameters - A Cross Sectional Study." *Annals of Biological Research* 5:40–48.

Aenumulapalli, G., D. Singh, and A. Chawla. 2017. "Effect of Flat Foot on Lower Limb and Lumbar Spine Biomechanics: A Systematic Review." *Journal of Bodywork and Movement Therapies* 21(4):868–75.

Anon. n.d. *Https://Www.Physio-Pedia.Com/File:Foot.Jpg*.

Aqueveque, Pablo, Enrique Germany, Rodrigo Osorio, and Francisco Pastene. 2020. "Gait Segmentation Method Using a Plantar Pressure Measurement System with Custom-Made Capacitive Sensors." *Sensors* 20(3):656. doi: 10.3390/s20030656.

Babu, D., and B. Bordoni. 2025. "Anatomy, Bony Pelvis and Lower Limb: Medial Longitudinal Arch of the Foot." in *StatPearls [Internet]*. Treasure Island (FL): StatPearls Publishing.

Banwell, H. A., S. Mackintosh, and D. Thewlis. 2014. "Foot Orthoses for Adults with Flexible Pes Planus: A Systematic Review." *Journal of Foot and Ankle Research* 7(1):23. doi: 10.1186/1757-1146-7-23.

Boerum, Drew. 2003. "Biomechanics and Pathophysiology of Flat Foot." *Foot and Ankle Clinics* 8:419–30. doi: 10.1016/S1083-7515(03)00084-6.

Bolgla, Lori A., and Terry R. Malone. 2004. "Plantar Fasciitis and the Windlass Mechanism: A Biomechanical Link to Clinical Practice." *Journal of Athletic Training* 39(1):77–82.

Bouden, C., Z. Ben Salah, M. Cheikh, and M. H. Elleuch. 2020. "Morphometric Analysis of the Medial Longitudinal Arch of the Foot: A Cadaveric Study." *Surgical and Radiologic Anatomy* 42(9):1055–61.

Buldt, A. K., I. Forner-Cordero, and S. C. Wearing. 2018. "Contact Area and Pressure Distribution of Flat, Normal, and High Arched Feet." *Gait & Posture* 62:192–98.

Cheung, J. T., M. Zhang, and A. K. Leung. 2004. "Biomechanical Effects of Plantar Fascia Release in the Pes Planus Foot." *Clinical Biomechanics* 19(9):903–8.

Dahle, A. W., D. L. Mueller, A. Delitto, and J. R. Stevenson. 1991. “Visual Assessment of Foot Type and Relationship of Foot Type to Lower Extremity Injury.” *Journal of Orthopaedic & Sports Physical Therapy* 14(2):70–74.

Deu, A., N. Maffulli, F. Oliva, and J. P. Furia. 2022. “Posterior Tibial Tendon Dysfunction: Current Concepts.” *Journal of Orthopaedic Surgery and Research* 17(1):1–11.

Franco, A. H. 1987. “Pes Planus and Pes Cavus: Analyses and Treatment.” *Journal of the American Physical Therapy Association* 67(5):688–94.

Hollman, John H., Eric M. McDade, and Ronald C. Petersen. 2011. “Normative Spatiotemporal Gait Parameters in Older Adults.” *Gait & Posture* 34(1):111–18. doi: 10.1016/j.gaitpost.2011.03.024.

Jennings, J., and J. C. Christensen. 2008. “A Review of the Static and Dynamic Function of the Plantar Aponeurosis.” *Journal of the American Podiatric Medical Association* 98(6):481–89.

Jeon, Eun-tae, and Hwi-young Cho. 2020. “A Novel Method for Gait Analysis on Center of Pressure Excursion Based on a Pressure-Sensitive Mat.” *International Journal of Environmental Research and Public Health* 17(21):7845. doi: 10.3390/ijerph17217845.

Jung, D. Y., J. Y. Kim, and O. Y. Kwon. 2011. “Change in Arch Height and Navicular Drop Following Gait Training in Athletes with Excessive Pronation.” *Journal of Sports Science & Medicine* 10(1):163–67.

Kelly, L. A., G. Lichtwark, and A. G. Cresswell. 2015. “Active Regulation of Longitudinal Arch Compression and Recoil during Walking and Running.” *Journal of the Royal Society Interface* 12(102):20141076. doi: 10.1098/rsif.2014.1076.

Khan, K. M., J. L. Cook, F. Bonar, P. R. Harcourt, and M. Astrom. 2013. “Histopathology of Common Tendinopathies. Update and Implications for Clinical Management.” *Sports Medicine* 27(6):393–408.

Kim, E. K. 2015. “The Effects of Flatfoot on Lower Extremity Injuries in Athletes.” *Journal of Physical Therapy Science* 27(10):3123–26.

Kodithuwakku Arachchige, S. H., S. Manivasagan, and B. S. Rajaratnam. 2019. “Prevalence of Flat Foot among Adults and Its Association with Musculoskeletal Pain.” *Journal of Physical Therapy Science* 31(12):999–1002.

Koutsogiannis, E. 1971. “Treatment of Mobile Flat Foot by Calcaneal Lengthening.” *Clinical Orthopaedics and Related Research* (75):94–96.

Kuhn, M. A., N. J. Shibley, and D. A. Austin. 1999. “Radiographic Changes in Flexible Flatfoot Deformity after In-Shoe Orthotic Treatment.” *Journal of Foot & Ankle Surgery* 38(6):403–9.

Levinger, P., W. Gilleard, and B. D. Coleman. 2010. “Relationship between Foot Posture and Lower Limb Kinematics during Walking.” *Gait & Posture* 32(4):569–73.

Ling, S. K., and T. H. Lui. 2017. “Posterior Tibial Tendon Dysfunction: Current Concepts and Treatment.” *Journal of Orthopaedic Surgery* 25(2):2309499017709598.

Liu, George, Michael Chen, and yonghua Chen. 2019. “When Joggers Meet Robots: The Past, Present, and Future of Research on Humanoid Robots.” *Bio-Design and Manufacturing* 2. doi: 10.1007/s42242-019-00038-7.

Loc, H. T., T. T. Tran, T. T. Mai, and T. T. Nguyen. 2015. “Immediate Effects of Kinesio Taping on Pain, Swelling, and Range of Motion in Patients with Acute Ankle Sprain.” *Journal of Physical Therapy Science* 27(10):3169–72.

Lugade, Vipul, and Kenton Kaufman. 2014. “Dynamic Stability Margin Using a Marker Based System and Tekscan: A Comparison of Four Gait Conditions.” *Gait & Posture* 40(1):252–54. doi: 10.1016/j.gaitpost.2013.12.023.

Luque-Suarez, A., S. Navarro-Ledesma, J. Painceira-Villar, and C. Rodriguez-Blanco. 2014. “Effects of Kinesio Taping on Ankle Sprain: A Systematic Review.” *Physical Therapy in Sport* 15(4):213–20.

McClay, I. S., and K. Manal. 1998. “Three-Dimensional Kinetic Analysis of Running: A Preliminary Investigation.” *Medicine and Science in Sports and Exercise* 30(8):1300–1309.

McClay, Irene, and Kurt Manal. 1998. “A Comparison of Three-Dimensional Lower Extremity Kinematics during Running between Excessive Pronators and Normals.” *Clinical Biomechanics* 13(3):195–203. doi: 10.1016/S0268-0033(97)00029-6.

McKeon, P. O., J. Hertel, R. A. Brammer, and I. Davis. 2015. “Functional and Performance Characteristics of Individuals with Chronic Ankle Instability.” *Journal of Athletic Training* 50(2):119–26.

Menz, H. B. 1998. “Alternative Techniques for the Clinical Assessment of Foot Pronation.” *Journal of the American Podiatric Medical Association* 88(3):119–29.

Mueller, Michael J., Jennifer V. Host, and Barbara J. Norton. 1993. “Navicular Drop as a Composite Measure of Excessive Pronation.” *Journal of the American Podiatric Medical Association* 83(4):198–202. doi: 10.7547/87507315-83-4-198.

Mulligan, E. P., and P. G. Cook. 2013. “First Metatarsophalangeal Joint Range of Motion and Plantar Pressure Differences in Pronated Feet: A Cadaver Study.” *Journal of Orthopaedic & Sports Physical Therapy* 43(1):32–37.

Murley, G. S., H. B. Menz, and K. B. Landorf. 2009. “Radiographic Evaluation of the Medial Longitudinal Arch: Comparison of Weightbearing and Nonweightbearing Techniques.” *Journal of the American Podiatric Medical Association* 99(2):112–18.

Okamura, K., H. Kimura, and M. Yamanaka. 2020. “Effect of Short-Foot Exercise on Navicular Drop and Plantar Pressure Distribution in Individuals with Flexible Flatfoot.” *Journal of Physical Therapy Science* 32(12):808–12.

Owings, T. M., and M. D. Grabiner. 2004. “Variability of Step Kinematics in Young and Older Adults.” *Gait Posture* 20(1):26–29. doi: 10.1016/S0966-6362(03)00088-2.

Perera, C. Smith S., and L. Coffman. 2016. “NUMBER OF STEPS NEEDED FOR RELIABLE GAIT VARIABILITY MEASUREMENT.” *The Gerontologist* 56(Suppl_3):335–36. doi: 10.1093/geront/gnw162.1366.

Pfeiffer, M., L. Cottrell, K. Ford, T. McPoil, and C. Payne. 2006. “Obesity and Flat Feet in Preschool-Aged Children: Cross-Sectional Study.” *BMC Pediatrics* 6(1):1–6.

Pita-Fernandez, S., C. Gonzalez-Martin, F. Alonso-Tajes, T. Seoane-Pillado, S. Pertega-Diaz, V. Gil-Guillen, and S. Perez-Garcia. 2017. “Prevalence of Flat Foot in a Random Population and Its Impact on Quality of Life and Disability.” *Journal of Pediatric Orthopaedics Part B* 26(6):509–14.

Raj, M. A., T. N. Mahabaleshwar, and H. Kumar. 2023. “A Biomechanical Analysis of the Human Foot Arch.” *Journal of Mechanics in Medicine and Biology* 23(01):2350002.

Rhea, Christopher K., Adam W. Kiefer, F. J. Haran, Stephen M. Glass, and William H. Warren. 2014. “A New Measure of the CoP Trajectory in Postural Sway: Dynamics of Heading Change.” *Medical Engineering & Physics* 36(11):1473–79. doi: 10.1016/j.medengphy.2014.07.021.

Ridola, C., and A. Palma. 2001. “The Biomechanics of the Foot.” *Foot* 11(4):211–18.

Ross, S. D. 1997. “Posterior Tibial Tendon Dysfunction.” *Clinics in Podiatric Medicine and Surgery* 14(4):773–81.

Shih, Y. F., C. Y. Chen, W. Y. Chen, and H. C. Lin. 2012. “Lower Extremity Kinematics in Children with and without Flexible Flatfoot: A Comparative Study.” *BMC Musculoskeletal Disorders* 13:31. doi: 10.1186/1471-2474-13-31.

Shin, H. S., N. S. Kim, and J. Y. Kim. 2019. “Comparison of Gait Patterns between Flexible Flat Foot and Normal Foot during Stance Phase.” *Journal of Physical Therapy Science* 31(1):108–11.

Staheli, L. T. 1987. “Pes Planus.” *Clinical Orthopaedics and Related Research* (225):17–21.

Standring, Susan. 2016. “Ankle and Foot.” Pp. 1418–51 in *Gray’s Anatomy,* edited by S. Standring. Philadelphia: Elsevier.

Starkey, C., and S. D. Brown. 2015. *Examination of Orthopedic & Athletic Injuries*. F. A. Davis.

Stolwijk, N. M., J. Duysens, J. W. Louwerens, Y. H. van de Ven, and N. L. Keijsers. 2013. “Flat Feet, Happy Feet? Comparison of the Dynamic Plantar Pressure Distribution and Static Medial Foot Geometry between Malawian and Dutch Adults.” *PLoS One* 8(2):e57209. doi: 10.1371/journal.pone.0057209.

Tateuchi, H., M. Wada, and N. Ichihashi. 2011. “Kinematic Analysis of the Foot during Running in Subjects with Flexible Flatfoot.” *Gait & Posture* 34(2):224–29.

Terrier, Philippe. 2012. “Step-to-Step Variability in Treadmill Walking: Influence of Rhythmic Auditory Cueing” edited by A. Lr. Thomas. *PLoS ONE* 7(10):e47171. doi: 10.1371/journal.pone.0047171.

Tome, J., A. Valero, and C. De-la-Cruz. 2006. “Electromyographic Activity of the Abductor Hallucis Muscle during Gait in Normal and Pronated Feet.” *Journal of Electromyography and Kinesiology* 16(5):458–64.

Tong, Jasper W. K., and Pui W. Kong. 2013. “Association Between Foot Type and Lower Extremity Injuries: Systematic Literature Review With Meta-Analysis.” *Journal of Orthopaedic & Sports Physical Therapy* 43(10):700–714. doi: 10.2519/jospt.2013.4225.

Trnka, H. J., and R. Ivanic. 2004. “Flatfoot in Children.” *EFORT European Federation of National Associations of Orthopaedics and Traumatology* 11(3):209–14.

Veltro, C., J. J. Branca, A. Vacca, and F. Paternostro. 2022. “The Foot: Anatomy Notes.” *Infermieristica Journal* 1(1):30–37. doi: 10.36253/if-179.

Wang, Shuaijie, Jessica Pitts, Rudri Purohit, and Himani Shah. 2025. “The Influence of Motion Data Low-Pass Filtering Methods in Machine-Learning Models.” *Applied Sciences* 15(4):2177. doi: 10.3390/app15042177.

Winter, D. A. 1995. “Human Balance and Posture Control during Standing and Walking.” *Gait and Posture* 3:193–214. doi: 10.1016/0966-6362(96)82849-9.

Zhai, Jun Na, Jue Wang, and Yu Sheng Qiu. 2017. “Plantar Pressure Differences among Adults with Mild Flexible Flatfoot, Severe Flexible Flatfoot and Normal Foot When Walking on Level Surface, Walking Upstairs and Downstairs.” *Journal of Physical Therapy Science* 29(4):641–46. doi: 10.1589/jpts.29.641.

Zhang, Li-Ying, Qi-Long Liu, Kit-Lun Yick, Joanne Yip, and Sun-Pui Ng. 2023. “Analysis of Diabetic Foot Deformation and Plantar Pressure Distribution of Women at Different Walking Speeds.” *International Journal of Environmental Research and Public Health* 20(4):3688. doi: 10.3390/ijerph20043688.

Zuil-Escobar, J. C., R. Valero-Alcaide, and D. López-López. 2018. “Reliability and Validity of the Navicular Drop Test: A Systematic Review.” *Journal of Physical Therapy Science* 30(11):1361–67.