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Gait analysis using IMUs for transtibial amputees using 3D printed prosthesis

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Gait analysis using IMUs for transtibial amputees using 3D printed prosthesis

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science

in

Bioengineering

by

Shriya Shetty

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2024

The thesis of Shriya Shetty is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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ABSTRACT OF THE THESIS

Gait analysis using IMUs for transtibial amputees using 3D printed prosthesis

by

Shriya Shetty

Master of Science in Bioengineering

University of California San Diego, 2024

Professor Falko Kuester, Chair

Professor Gert Cauwenbergs, Co-Chair

Currently 1.6 million people have undergone limb amputation in the US alone and the dependency on lower limb prosthesis has been increasing for its many advantages. Gait analysis forms the backbone of post prosthesis attachment rehabilitation. In this study, a gait analysis module is developed using IMUs and FSRs, to collect and analyse gait parameters in real-world conditions. The sensor data was validated against a ground truth established by mounting the

module on a 3D printer extruder head. Post processing of the data is done using a Madgwick Filter. We can accurately determine gait parameters like stride length, step length, time of stance and swing phases and cadence in a subject with normal gait. The cadence value obtained was 216 steps/min and the stride length was found to be 0.9m, which falls within the normal range for the subject's age.

Introduction

The human gait is a complex, dynamic process that plays a fundamental role in maintaining mobility, balance, and overall physical health. For individuals who have undergone lower limb amputation, the loss of this natural gait presents significant challenges, impacting not only their physical capabilities but also their psychological and social well-being. Prosthetic limbs serve as critical tools in restoring some of the lost function, enabling amputees to regain independence and participate more fully in daily life. The advent of 3D printing technology has introduced new possibilities for prosthetic design and customization. 3D printed prostheses offer a level of flexibility and personalization that was previously unattainable, allowing for rapid prototyping and the production of bespoke devices tailored to the specific needs of each user. However, the effectiveness of a prosthetic limb is not solely dependent on its design but also on how well it is integrated into the user's life, particularly through rehabilitation and continuous adaptation to the prosthesis.

Traditional methods of gait analysis, such as visual observation and the use of stationary equipment like motion capture systems and force plates, have provided valuable insights into the biomechanics of walking. However, these methods often fall short in capturing the full spectrum of an amputee's gait, particularly in real-world conditions. The limitations of these techniques highlight the need for more advanced, flexible, and accessible approaches that can accurately assess gait in natural environments. Wearable technology, specifically Inertial Measurement Units (IMUs), has emerged as a promising solution, offering the ability to monitor gait continuously and unobtrusively.

IMUs are small, portable sensors that measure acceleration, angular velocity, and orientation, providing detailed data on the movement of the body in three-dimensional space. When combined with other sensors, such as Force Sensitive Resistors (FSRs), IMUs can deliver comprehensive spatiotemporal data on gait, which is crucial for understanding the intricacies of prosthetic-assisted walking. This data can be used not only to assess the effectiveness of a prosthesis but also to inform modifications that enhance comfort, functionality, and long-term health outcomes. These sensors allow for continuous monitoring of gait in various environments, capturing data that is more representative of everyday activities. This capability is particularly important for transtibial amputees, whose prosthetic needs may vary greatly depending on their daily routines and physical demands. By providing real-time feedback, IMUs can help clinicians and prosthetists make more informed decisions about prosthetic design and adjustments, leading to better alignment, fit, and overall satisfaction for the user.

This combination of advanced sensor technology and customizable prosthetics holds the potential to revolutionize the field of prosthetic rehabilitation, making it more effective, accessible, and responsive to the needs of amputees. In this context, the present thesis explores the application of IMUs in spatiotemporal gait analysis for transtibial amputees using 3D printed prostheses. By developing and validating a novel gait analysis module, this research aims to provide a more precise and practical tool for assessing and improving prosthetic-assisted gait. The insights gained from this study contribute to the development of more effective prosthetic devices and rehabilitation strategies, ultimately improving the quality of life for individuals living with limb loss. It is intended for long endurance gait as well as life-cycle analysis of the prosthetic device.

Chapter 1

Background and Significance

Currently, more than 1.6 million persons are living with limb loss in the United States, with projections indicating a staggering increase to 3.6 million by 2050 [100]. Of these cases, approximately 85% of the amputations are of the lower extremities [6]. While traditional causes such as vascular diseases (diabetes mellitus [30][96][54], peripheral arterial disease [30][31][36]), tumors [100][53] and malignancy of the bone and joint [30][32], continue to be prevalent, it is noteworthy that traumatic incidents stemming from sociopolitical conflicts, notably wars [33], have emerged as significant contributors in recent times. Affordable and customizable prostheses, catering to amputees of all socioeconomic backgrounds, such as 3D printed prosthetic limbs (Figure 1.1)[27], not only restore the amputee's mobility and independence, but also notably enhance their quality of life (QoL) and mitigate secondary health issues [91]. Central to the efficacy of prosthetic integration is the rehabilitation process following attachment. Post-amputation rehabilitation is dedicated to reinstating functional autonomy in daily activities and facilitating a return to pre-amputation levels of engagement [45][68]. It is imperative to recognize that substandard or insufficient rehabilitation may impede the successful adaptation to the prosthetic device, ultimately hindering the wearer's adjustment process [101]. A crucial aspect of lower limb prosthesis rehabilitation is the examination of gait patterns. Analysing the gait of an amputee using a prosthetic device provides valuable insights into various potential challenges, including excessive load on sound limb [34], socket-related issues [51], metabolic

Figure 1.1. Example of 3D printed prosthesis [27].

cost of ambulation [81][73] and gait asymmetry [18][66][34]. Additionally, it provides significant feedback for making adjustments to the prosthetic design [72][17][26]. Long-term asymmetrical gait in lower limb amputees may result in physiological impairments, which can subsequently lead to mental and social challenges [9][37][62][78].

Historically, gait analysis was predominantly conducted through visual observation by clinicians, which, while valuable, is inherently subjective and prone to errors [64]. Without doubt, an objective approach was required for a more reliable and precise analysis of the gait. Hence, to enhance accuracy, methods such as motion capture systems [65][20][92] and force plates [3][90][95][48] were developed.

Motion capture systems use markers placed on the body to track movement in a controlled environment [65][63], providing data on kinematics. Although the assessment requires the need for a specialized facility and bulky ensembles, are time consuming and not practical for routine clinical use. Moreover, results may be affected by displacement of the markers with movement [76]. While motion capture techniques evolved to markerless-based gait analysis, the data collected showed inaccuracies relating to pose estimation algorithms [93], thereby providing incorrect results. They are also an extremely expensive option as the assembly includes expensive videography equipments and cameras [77].

Force plates measure the ground reaction forces during walking [85], offering insights into the dynamics of gait [28][48]. One of the major drawbacks of this technique was that the subjects had limited stride lengths since they had to walk on the centre of the force plates [22]. They also fail to reflect real-world conditions and do not capture the full spatiotemporal parameters of gait, which are crucial for a comprehensive analysis.

In recent years, wearable technology, such as inertial measurement units (IMUs), has emerged as a promising alternative [13][10][46][12]. IMUs are small, lightweight sensors [23][97] that can be easily attached to the body, allowing for continuous monitoring of gait in natural environments [55].

In this thesis, a combination of IMU sensors and Force Resistive Sensors (FSRs) is used to develop a module which makes up for a powerful gait analysis tool that provides detailed spatiotemporal data, which is vital for evaluating prosthetic age and performance, without the need for extensive cumbersome bodysuits or heavy and expensive hardware.

Chapter 2

Specific Aims

Gait imperfections after the fitting of below-the-knee prostheses is a common problem faced by amputees and prosthetists alike. These imperfections may arise due to several factors such as alignment differences, improper socket fit and asymmetrical limb lengths, which can have cascading impacts on the residual limb's vascular health, potentially leading to complications like infections, stump pain and discomfort, and ultimately prolonging the rehabilitation period of the prosthesis or leading to its absolute failure. Furthermore, the sound limb may undergo unnatural compensatory maneuvers, exacerbating the negative impact on the patient's quality of life despite prosthetic attachment.

A method to identify and evaluate these abnormalities associated with prosthetic design hence becomes crucial. Early detection and periodic evaluations will enable recognizing potential risk factors and promote timely adjustments like modifications to the socket design, prosthetic length, and alignment correction. Leveraging the flexibility and customization capabilities inherent in 3D-printed prostheses allows for expedited and cost-effective implementation of these adjustments.

Inertial Measurement Units (IMUs), commonly used in navigation systems for their ability to measure and track the motion and orientation of objects in three-dimensional space, emerge as a promising option for human gait analysis. The primary hypothesis of this thesis posits that IMUs, when paired with Force Sensitive Resistors (FSRs), can provide precise integral information about the nuances of human gait. The objective of this thesis is to analyse the prosthetic-assisted gait through information collected from the IMUs and make necessary modifications to the prosthesis to achieve a symmetrical and anatomical gait. We plan to achieve the primary objective of this thesis through the following specific aims:

1. **Development and validation of a gait analysis module using IMUs** To design and implement a module, using IMUs at the shank and FSRs at the heel, that can be easily fitted on the sound as well as residual limbs to collect common gait parameters from amputees under several test conditions. The results will then be calibrated and validated against a ground truth. The IMU units will be fine-tuned to improve accuracy in capturing integral gait parameters.

2. **Assessment of gait parameters** Obtain results from the calibrated electrical module to understand and investigate abnormalities in gait. This will provide a comprehensive understanding of how corrective measures can be employed to treat different adversities being caused due to abnormal gait mechanics. Also use infirmation for long endurance gait measurement and life-cycle assessment of the prosthesis.

Upon the completion of these studies, we shall have a robust and precise tool for subsequent gait analysis studies. Building upon this, major consequences of improper gait can be avoided at the root by identifying problem areas and saving the patients from having a traumatic experience, and enabling a smooth transition to a better life. These aims hold the potential to collectively advance the field of prosthetic rehabilitation.

Chapter 3

The Human Gait

3.1 Gait Cycle

Human gait is a cyclical movement involving limbs used for locomotion, and the study of this movement and its associated dynamics is known as gait analysis [82] [6]. This cycle can be divided into two main phases: **stance and swing**, each comprising sub-phases that describe specific actions and positions of the lower limbs during regular gait Figure 3.1. Understanding these phases and their respective positions is crucial for assessing gait abnormalities, designing effective prosthetics, and implementing targeted rehabilitation therapies.

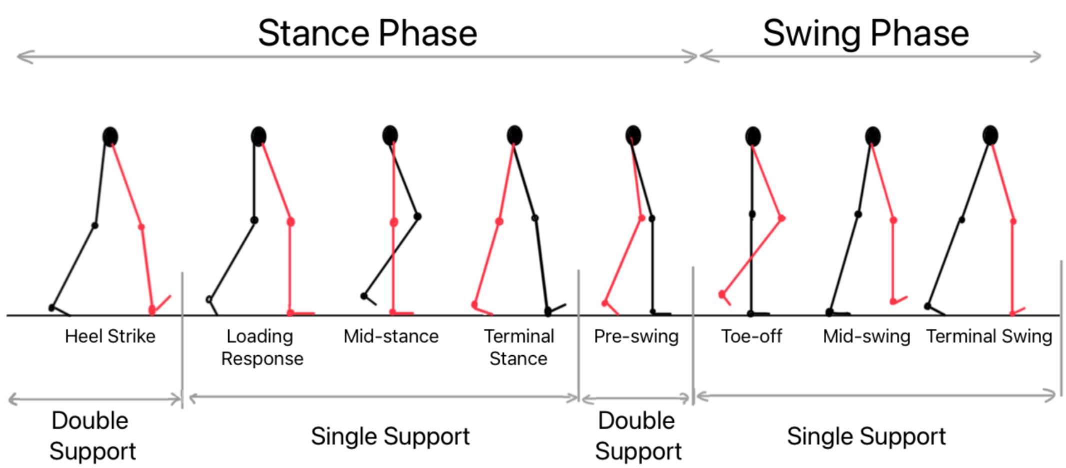

Figure 3.1. The Human Gait Cyle.

3.1.1 Stance Phase

The stance phase accounts for approximately 60% of the gait cycle and begins the moment one foot contacts the ground. In this phase, both feet are in some contact with the ground, hence there is **double support**. It is further divided into the following sub-phases:

1. Initial Contact (Heel Strike): This is the moment when the heel of the foot first touches the ground. It marks the beginning of the stance phase.

2. Loading Response: Following initial contact, weight is transferred onto the forward foot. This phase is characterized by slight flexion of the knee to absorb the impact.

3. Midstance: This occurs when the body's weight is directly over the stance limb, and the foot is flat on the ground. The limb supports the body's weight entirely on its own during this phase.

4. Terminal Stance: As the heel of the stance foot begins to lift off the ground, the body prepares for the transition from stance to swing. Weight shifts forward, and the toes remain in contact with the ground.

5. Pre-swing (Toe-off): This final phase of the stance occurs as the toes leave the ground, propelling the body forward and transitioning to the swing phase of the opposite foot.

3.1.2 Swing Phase

The swing phase follows the stance phase and occupies about 40% of the gait cycle. It involves lifting the foot off the ground and moving it forward, hence there is only **single support**. It is also subdivided into three phases:

1. Initial Swing: This phase starts as the foot lifts off the ground and the limb begins to move forward.

2. Mid Swing: During this phase, the foot moves directly beneath the body as the limb swings forward, preparing for the next step.

3. Terminal Swing: This phase completes as the swinging limb decelerates and the foot prepares to make contact with the ground, marking the beginning of the next stance phase.

The swing phase and the stance phase together comprise one **stride** of the entire gait cycle. The accurate assessment and analysis of these phases are essential for understanding individual gait characteristics and identifying deviations from normal gait patterns. For individuals with gait abnormalities, such as those resulting from lower limb amputations, detailed gait analysis can inform the design of prosthetic devices and rehabilitation strategies that restore functional and efficient walking patterns. This holistic understanding not only improves the physical alignment and mechanics of walking but also enhances the overall mobility and quality of life for individuals relying on prosthetic support.

3.2 Gait Parameters

The gait cycle can be quantized using certain gait parameters [67][52]. Each parameter plays a crucial role in understanding and analyzing human locomotion. They provide insights into the biomechanical and functional aspects of walking, which can help in diagnosing abnormalities, planning treatments, and monitoring rehabilitation progress. Following list of parameters are essential for any gait analysis procedure,

1. **Stride Length**: The distance covered in one complete stride, measured from the heel strike of one foot to the heel strike of the same foot again. It indicates the efficiency of the gait and balance. Shortened stride lengths can suggest joint stiffness, pain, or neuromuscular issues. It is useful in diagnosing conditions like Parkinson's disease, where stride length is typically reduced [21].

2. **Step Length**: The distance between the point of initial contact of one foot and the point of initial contact of the opposite foot. It assesses symmetry between the left and right legs. Asymmetrical step lengths can indicate limb discrepancies or unilateral strength deficits. It is helpful in identifying gait abnormalities post-stroke or in individuals with musculoskeletal injuries [71][80].

3. **Cadence**: The number of steps taken per minute. It's a measure of the rate of stepping. It reflects the rhythmic and temporal aspects of gait. Changes in cadence can affect overall mobility and energy efficiency. Lower cadences may be observed in conditions affecting mobility and balance, such as muscular dystrophy [8][75][38].

4. **Walking Speed**: The overall speed of walking of the subject. It is a good overall indicator of a person's functional ability and health status. Reductions in walking speed can be a sign of aging or health decline, common in neurological disorders [15][40].

5. **Stride Width**: The side-to-side distance between the paths of the left and right feet during walking. This parameter provides information about base of support and balance. Narrower or wider bases can be compensatory mechanisms for maintaining stability. It is useful in assessing individuals with balance issues, such as those recovering from a traumatic brain injury [61][24].

6. **Stride Time**: The time taken for a complete stride - a combination of the stance phase time and swing phase time. Variations can reveal timing issues related to neurological conditions, like ataxia or spasticity [56].

In this thesis, we analyse gait using the above mentioned parameters in order to obtain a comprehensive profile of the subject's gait, enabling clinicians and prosthetists to make a customised rehabilitation plan for the subject.

Chapter 4

Gait Analysis

Gait analysis is the systematic study of human walking [82]. It involves the measurement and assessment of the body's movement and mechanics during locomotion, primarily focusing on the lower limbs. Gait analysis is used to understand the biomechanics of walking, including the timing and coordination of the limbs, the forces exerted by and on the body, and the efficiency of movement.

Human gait analysis is pivotal in a wide array of applications, reflecting its fundamental role in health and mobility [84]. Accurately analyzing gait is crucial not only for diagnosing and treating locomotive disorders but also for optimizing rehabilitation strategies [11][25], customizing prosthetics [35][74], and even preventing injuries in athletics [94][57]. In clinical settings, gait analysis is instrumental in the early diagnosis and monitoring of diseases that affect mobility, such as multiple sclerosis [19][39][83] and Parkinson's disease [29][42][21][16]. For the elderly, it provides valuable insights into balance and stride, which can help in developing interventions to prevent falls [14][69]. Moreover, in the realm of sports science, it assists athletes in enhancing their performance and avoiding injuries by fine-tuning their biomechanics [47][82]. Thus, the effective study and analysis of gait not only improve clinical outcomes but also significantly enhance individuals' quality of life by addressing fundamental aspects of movement and stability.

4.1 Evolution of Gait Analysis Methods

Human gait analysis has significantly evolved over the decades, transitioning from simple observational techniques to advanced wearable and non-wearable technology-driven methods [64][79] (Table 4.1), each contributing uniquely to our understanding of human locomotion.

Initially, gait analysis was predominantly based on visual observation by clinicians [47]. This method, relying solely on the expertise and subjective assessment of physical therapists or physicians, offered an immediate and cost-effective way to identify obvious gait abnormalities. However, its reliance on human judgment made it inherently subjective, with considerable variability in assessments. The limitations of the human eye in detecting subtler biomechanical issues also meant that many nuances of gait pathology went unnoticed.

The introduction of videography marked a significant advancement in gait analysis [86][49]. By recording gait cycles on video, clinicians were able to observe and analyze movement patterns in slow motion, providing a more detailed overview than mere observation. This technique improved the accuracy of visual assessments and allowed for a historical comparison over time. Despite these advantages, videography still relied on expensive equipment and laboratory settings, limiting its practical and economical use.

The development of instrumented treadmills [70] and pressure mats [50][59] introduced a more scientific approach to gait analysis. These devices could capture precise data on foot placement, timing, and pressure distribution throughout the gait cycle, providing quantitative insights that were not previously possible. This technology was particularly useful in evaluating the effectiveness of foot orthotics and prosthetic adjustments. However, its use was confined to laboratory settings, which did not necessarily reflect a person's natural walking environment, and the systems required significant investment and space.

A breakthrough in gait analysis came with the adoption of motion capture systems [98][58][63], which use body-worn markers or markerless technology to track movement in three dimensions. Employed extensively in both research and clinical settings, these systems

Table 4.1. Summary of Gait Analysis Technologies

Technology	Advantages	Limitations
Visual Observation	Immediate, cost-effective	Subjective, misses subtle issues
Videography	Detailed observation, historical comparison	Expensive, requires lab settings
Instrumented Treadmills	Quantitative data, useful for orthotics/prosthetics	Confined to labs, costly, space-intensive
Pressure Mats	Detailed foot pressure data	Limited to controlled environments
Motion Capture Systems	High accuracy, full-body analysis	Costly, complex setup, specialized environments required
Mobile based tracking	Continuous data collection, personalized assessments	Not accurate, personal information security issue, heavy dependency on user
Wearable Sensor Technology	Continuous data collection, real-world applicability, machine learning integration for personalized assessments	Calibration challenges, potential sensor drift issues

offered a high level of accuracy in measuring spatial and temporal aspects of gait. They enabled a detailed analysis of not just the lower limbs but the entire body's mechanics during movement. Despite their precision, motion capture systems were costly, required specialized environments, and involved complex setup and lengthy data processing, making them less accessible for routine clinical use.

The advent of mobile-based gait tracking represents a notable advancement in gait analysis technologies [99], leveraging the widespread availability and capabilities of smartphones and portable devices. However, mobile-based gait tracking also faces challenges such as potentially reduced accuracy compared to specialized equipment, dependence on user compliance for effectiveness, and concerns regarding data security and privacy.

4.2 Latest Trends in Gait Analysis

The recent shift towards wearable sensor technology [87][88], including inertial measurement units (IMUs) [41][44][60], has democratized gait analysis further. These devices, which can be worn on the body, allow for the assessment of gait dynamics in real-world settings. They provide continuous data collection over extended periods, making them invaluable for monitoring changes in gait over time and in various environmental contexts. While the need for precise calibration in such devices has always been a challenge, sophisticated data processing capabilities have helped counter errors due to drifts in the sensors. These involve the integration of machine learning algorithms in post processing. They large datasets from wearable sensors to predict, classify, and potentially correct gait abnormalities in real-time. This promises highly personalized assessments and interventions, adapting to individual walking patterns and offering potential corrections or rehabilitation strategies.

In this thesis, we have developed a gait analysis module using an IMU sensor and Force Sensitive Resistors, and robust post processing algorithms, with an aim to capture precise data while not compromising on practicality of use and cost.

Chapter 5

Materials and Methods

5.1 Materials

In this study, a combination of hardware and software tools was employed for the spatiotemporal analysis. Each component was carefully selected based on its functionality, ease of integration, and suitability for capturing the complex dynamics of human gait.

5.1.1 Hardware

Central to the system is the high resolution BNO055 Inertial Measurement Unit (Bosch Sensortec [4]), a 9-axis absolute orientation sensor which works by detecting motion including the kind, rate, and direction of that motion using a combination of accelerometers, magnetometers and gyroscopes [43]. The BNO055 features an onboard processor that fuses sensor data, minimizing drift and providing reliable real-time orientation data. The measurement frame of the IMU sensor is fixed to the orientation of the shank of the patient, where it is placed. Two round 12.7mm diameter capacitive Force Sensitive Resistors (FSR) are integral to acquiring measurements of heel strike and toe off as they exhibit a decrease in resistance when an increasing force is applied to their surface. This module uses two FSRs - one for the toe-off measurement and one for the heel strike measurement. They are chosen for their pointed accuracy and thin structure, providing flexibility to fit into the footwear of the subject without causing them any discomfort. The use of two FSRs allows for a detailed analysis of the heel-to-toe transition during walking and provides real-time feedback on pressure distribution. The weMos Lolin32 microcontroller [2] serves as the operational hub of the system, handling data input from both the IMU and the FSRs. Refer to Figure 5.1 for the circuit diagram. Its role extends beyond basic data processing; its built-in Wi-Fi and Bluetooth capabilities facilitates wireless transmission of the gait data to external devices for real-time analysis. Its low power consumption extends battery life, which is crucial for continuous monitoring over extended periods. This module uses one microcontroller board as the ”Receiver” board or the Master Board which is connected to the laptop. All other gait analysis modules - microcontroller boards with IMU and FSRs enclosed - are called the ”Sender” Boards and transmit data to the Receiver Board wirelessly through the weMos Lolin32’s WiFi 802.11 b/g/n module (Figure 5.5). The Sender microcontroller Boards are each powered by a sleek 3.7V rechargeable battery pack. The entire assembly is housed in a compact 3D printed enclosure (Figure 5.2). The compact size of the module allows for easy integration into an unobtrusive gait analysis system without adding bulk to the wearable device.

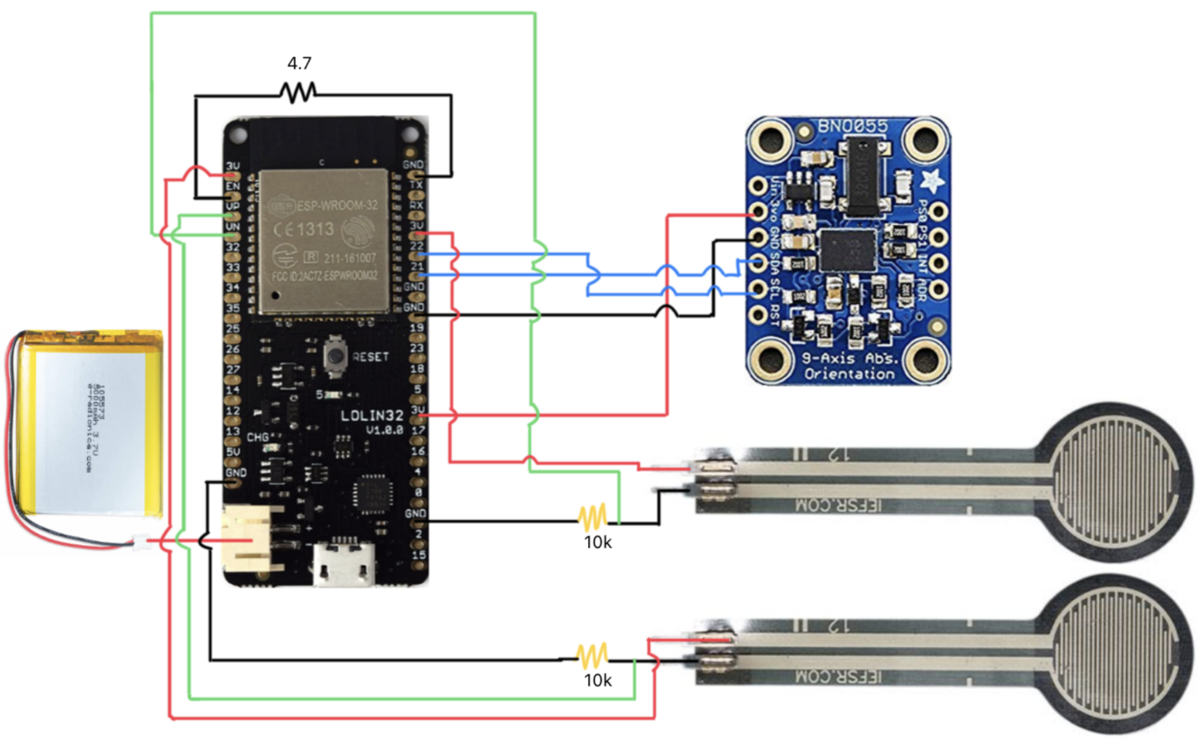

Figure 5.1. Circuit Diagram

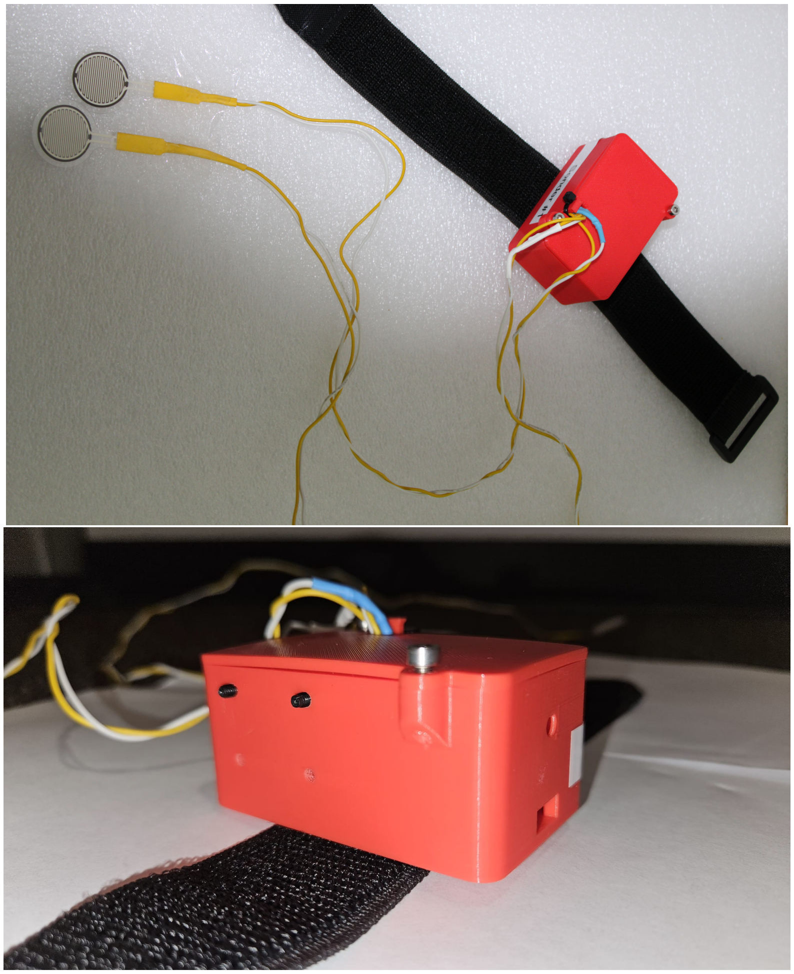

Figure 5.2. 3D printed casing of the gait analysis module which houses the sender microcontroller, IMU sensor, battery source, and two FSRs extending from the bottom, (a) Top View (b) Side View.

5.1.2 Software

On the software side, Arduino Integrated Development Environment (IDE) [1] is used specifically to program the weMos Lolin32, enabling precise control over how the data from the IMU and FSRs are collected and handled. The IDE supports a wide range of libraries, including those for interfacing specifically with the BNO055 IMU sensor like the Adafruit BNo055 Library.

For the sake of data acquisition, an interface was created (Figure 5.3) using the Processing 4 software [5]. This interface enables visualization of whether a wireless connection was established between the receiver board and the sender boards attached to the subject's shanks via the microcontroller's WiFi module. Once connected, it helps record the data from the experiment and save it locally using a file name of choice. It also helps visualise the orientation of the IMU as it moves in real-time. Post processing and manipulation and visualization of the collected data was done using Python.

(a) (b)

Figure 5.3. Data acquisition interface using the Processing 4 software, (a) The interface gives you an option of boards to select from, (b) When connected, the status of the corresponding boards turn green; can record the data in a file named by your choice.

This strategic approach to component functionality ensures that the system functions as a unified and synergistic tool, rather than merely a collection of disparate advanced technologies. By integrating each component with a clear purpose, the system is designed to work harmoniously, enhancing its effectiveness and reliability. This cohesive design is not just about technological sophistication; it is about delivering tangible benefits that significantly improve the quality of life for its users. The focus on seamless integration and purposeful design ensures that each part contributes meaningfully to the overall goal, making the system not only innovative but also profoundly user-centered.

5.2 Placement of the module

The gait analysis module - IMU housed with a weMos Lolin32 sender microcontroller, battery pack and two FSRs, in a 3D printed encasing - is placed anteromedially on the shank of the test subject and is secured in place using Velcro straps (Figure 5.4). Extending from the central unit, the FSRs are carefully aligned under the foot; one is placed at the heel and the other under the toe, each secured using adhesive tape to ensure consistent contact with the foot. The subject is then asked to don their usual footwear, preferably shoes, to simulate typical walking conditions.

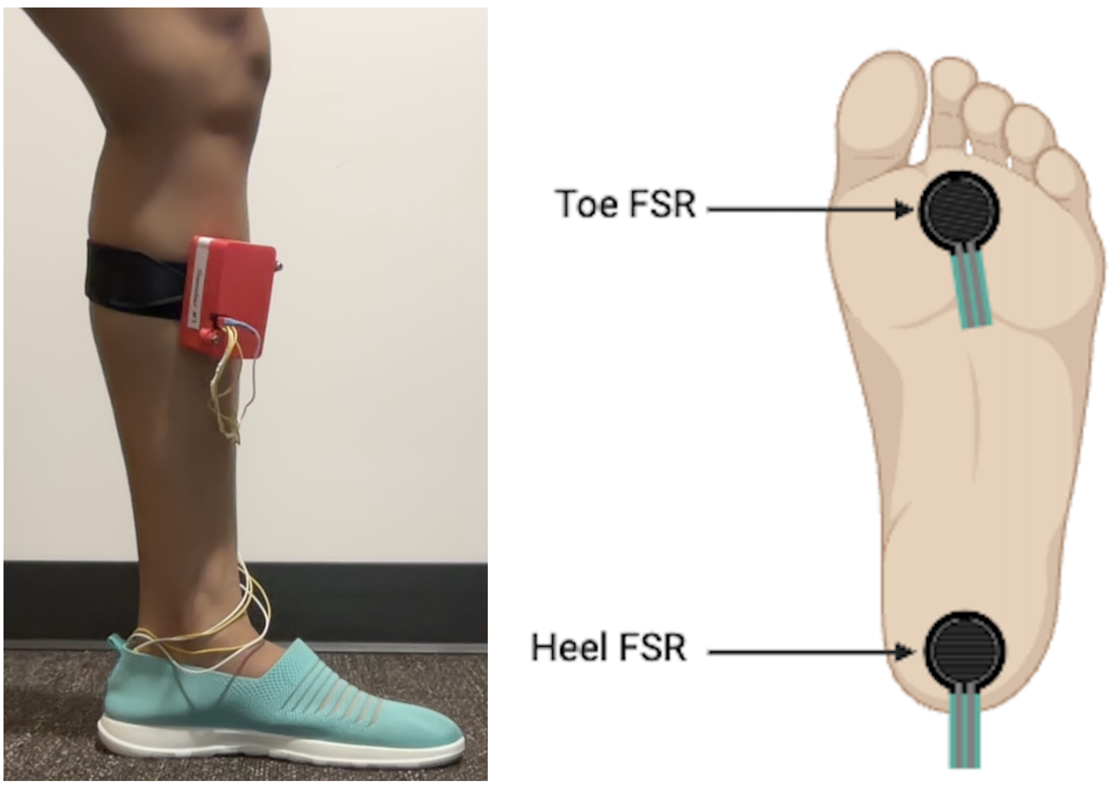

Figure 5.4. (a) The module positioned anteromedially on the shank of the test subject, with the tow and heel FSRs extending down inside the footwear of the subject. (b) Placement of the FSRs on the toe and heel of the feet of the subject.

The receiver board is connected to a processing unit (laptop) and receives data from multiple gait analysis modules remotely in real-time (Figure 5.5). This placement strategy ensures that the gait analysis module integrates seamlessly into the subject's natural walking environment without altering or hindering their natural gait pattern. The lightweight design and strategic positioning of the components allow for normal movement, thus ensuring that the data collected accurately reflects true gait dynamics under typical usage conditions, without any artificial influence from the device itself.

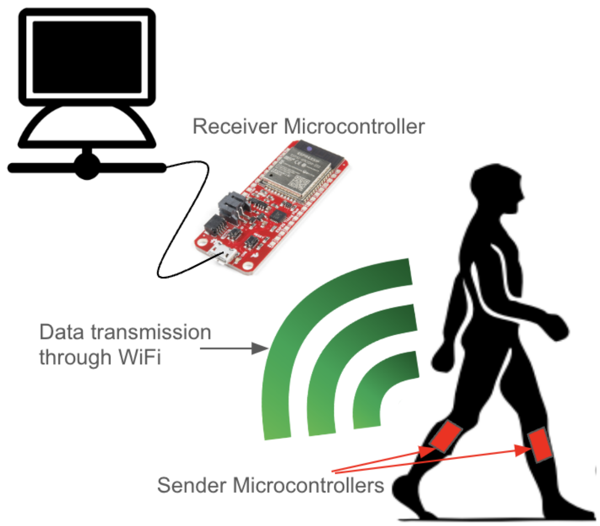

Figure 5.5. Test data being transmitted wirelessly through WiFi from the sender microcontrollers (encased in the red 3D printed cases worn by the subject) to the Receiver microcontroller connected to the computer.

Chapter 6

Experimental Setup

6.1 Establishing a Ground Truth

IMU sensors are famously infamous for collecting dirfts in readings over long periods of time. Drifts in IMU sensor readings occur due to the gradual accumulation of small errors in the sensor data over time, primarily due to factors like sensor noise, temperature changes, or biases in the accelerometers and gyroscopes. These errors cause deviations from accurate measurements, affecting the long-term accuracy of position and orientation tracking. Drift can be particularly problematic in long-duration measurements, as the errors compound without external reference points. Therefore, it becomes extremely important to validate the readings collected from the sensor against a ground truth.

For this, we mounted our gait analysis module on to the extruder head of a 3DP Printer. A set trajectory was defined at a known speed for the extruder, so we have a comparison point for our IMU readings. The readings, as expected, were noisy and differed from what was expected. For starters, the IMU's frame of reference was different from the global frame of reference (Figure 6.1(a)). Secondly, acceleration due to gravity (g-force) altered accelerometer readings in the global y-direction (Figure 6.1(b)). Both of these issues were countered using the Madgwick filter [7]. The Madgwick filter rotates the IMU coordinate system to the global coordinate system using the magnetometer data and also eliminates acceleration due to gravity. Thirdly, after a span of approximately 7ms, drifts were observed in the readings (Figure 6.1(b)). Sophisticated algorithms using Python were used to eliminate these drifts.

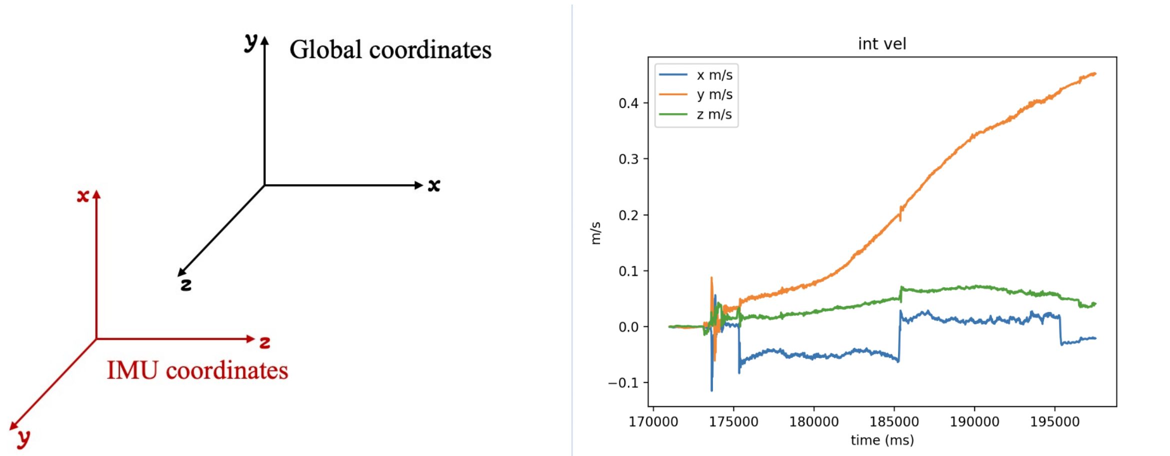

Figure 6.1. (a) The IMU frame of reference is different from the global frame of reference. (b) Altered readings in y-direction due to gravity acceleration and drifts in the z-direction.

The module was again mounted on the extruder head and the experiment was repeated. This time, the IMU readings were very close to the actual expected readings (Figure 6.2).

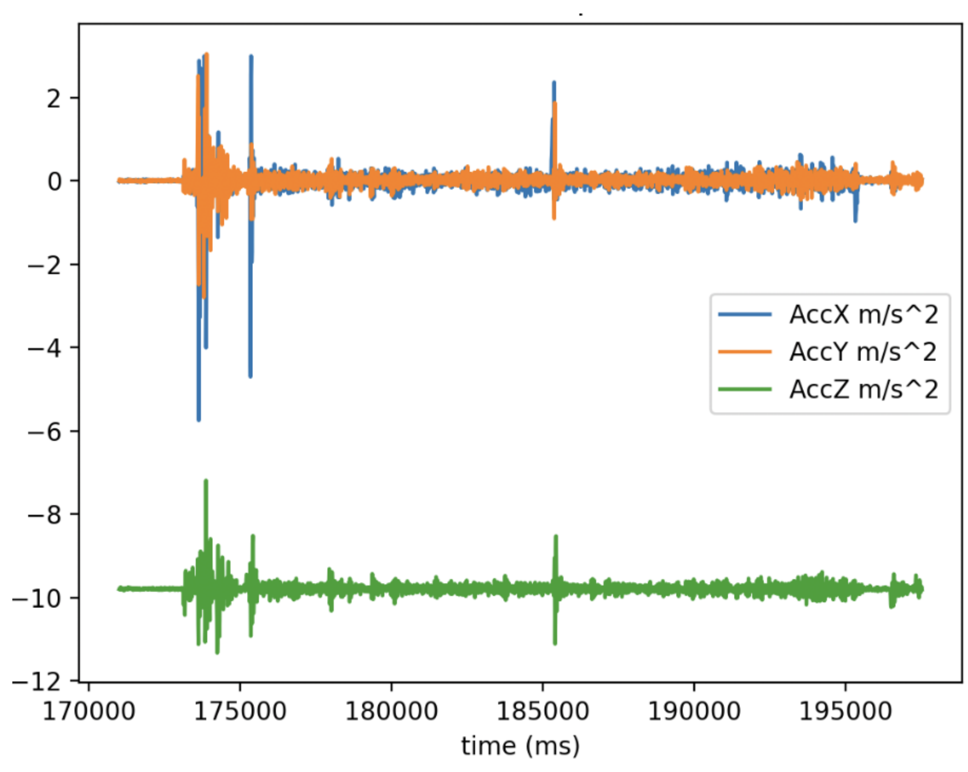

Figure 6.2. IMU data corresponding to expected data.

Now that the ground truth is established, we go ahead and collect gait readings from test subjects to satify the aims of this thesis.

6.2 Gait Analysis Experiment

Subject (Female, 26) with no known physical or mobility abnormalities and what can be considered a ”normal gait”, was chosen. They were made to wear the gait analysis modules anteromedially on each of their shanks, secured by Velcro straps as described in Figure 5.4. Measures were taken to ensure that the modules are secured tight and are not sliding down during the experiment. FSRs were ensured in their respective positions using clear tape.

A 4 meter long pathway was defined, with markings to indicate the ”Start” line and the ”Finish” line. Once the modules were secured, the subject was made to stand behind the Start line. As the recording began in the data acquisition software, the subject was asked to stand stationary for 2 seconds, after which they were instructed to walk till the Finish line as they normally would. Upon reaching the Finish line, the subject was asked to stand stationary again for a few seconds. After this, the recording was stopped (Figure6.3. This entire process was repeated thrice.

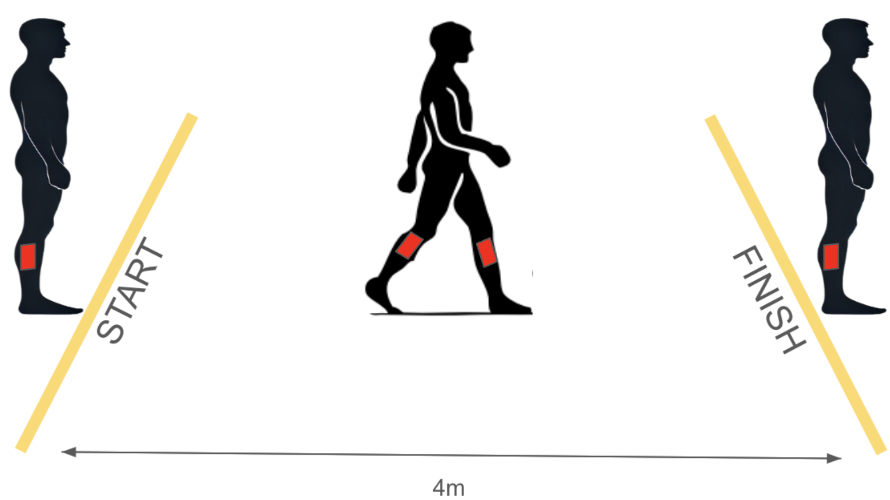

Figure 6.3. Experimental Setup; Initially the subject is asked to stand at the Start line for 2 seconds after the recording begins; then walk till the Finish line (4m away) and again stand stationary for another 2 seconds before concluding the recording.

Chapter 7

Results

All the data collected is first cleaned in a pre-processing algorithm as used for the ground truth data, for further processing and extracting the parameters that we are interested in for this study. We first plot the data acquired from the heel FSRs as the spikes in this data can lead us to several of the parameters - heel strike, step length, time of swing phase, time of stance phase, and will also help us visualise the gait pattern of the subject. The heel FSR data for both the left and the right foot is as shown in Figure 7.1.

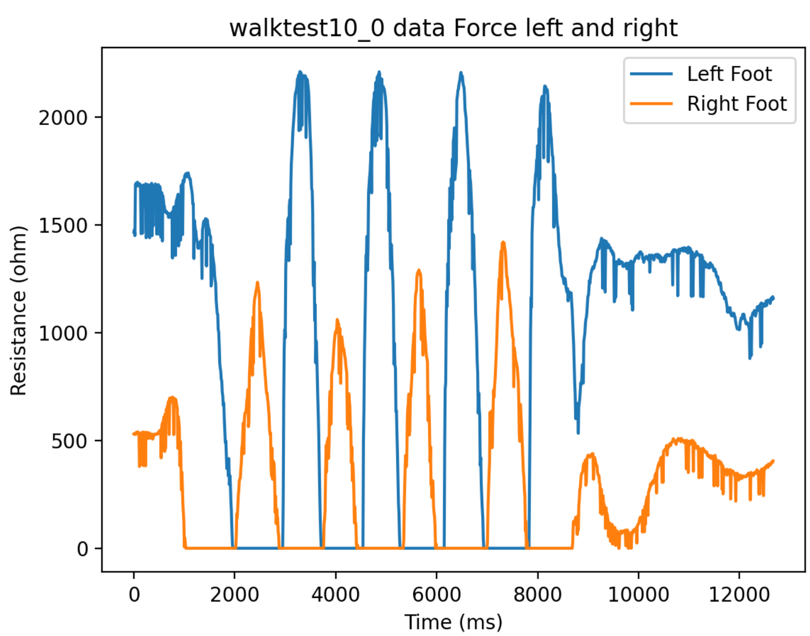

Figure 7.1. Data from the Heel FSRs of both feet.

An FSR value changes in response to applied pressure. When no pressure is applied, the sensor exhibits very high resistance, often exceeding 1MΩ, effectively reading as infinite. As pressure increases on the sensor's surface, the resistance between its terminals decreases. Conversely, when the pressure is removed, the resistance returns to its initial high value. In Figure 7.1, each instance of zero value for either of the feet indicates a step taken. It can be observed that the left foot (blue), took four steps to cover the distance set in the experiment. The right foot (orange) took five steps. It can also be observed that when one of the foot is on the ground (resistance is zero), the other foot is off ground (resistance is non-zero), with slight overlaps of zero values indicating the heel strike phase of the gait cycle.

We now average the data in a way to find the heel strike instances for both feet. From Figure 7.2 it is clear that the heel strikes for both feet are at regular intervals (∼1.3 seconds), another indication of normal gait.

Figure 7.2. (a) The left foot heel strike instances. (b) The right foot heel strike instances.

We shall now analyse the IMU data. According to the gait cycle as shown in Figure 3.1, we should ideally observe increasing acceleration in the heel-strike and loading response phases, constant velocity (or zero acceleration) in the mid-stance phase and deceleration or reducing acceleration in the terminal stance and pre-swing phases. Refer to Figure 7.3 to see the plot of the raw acceleration data obtained from the IMU in all three directions just for the left foot.

We observe the increasing accelerations right after the spikes which indicate the heel-

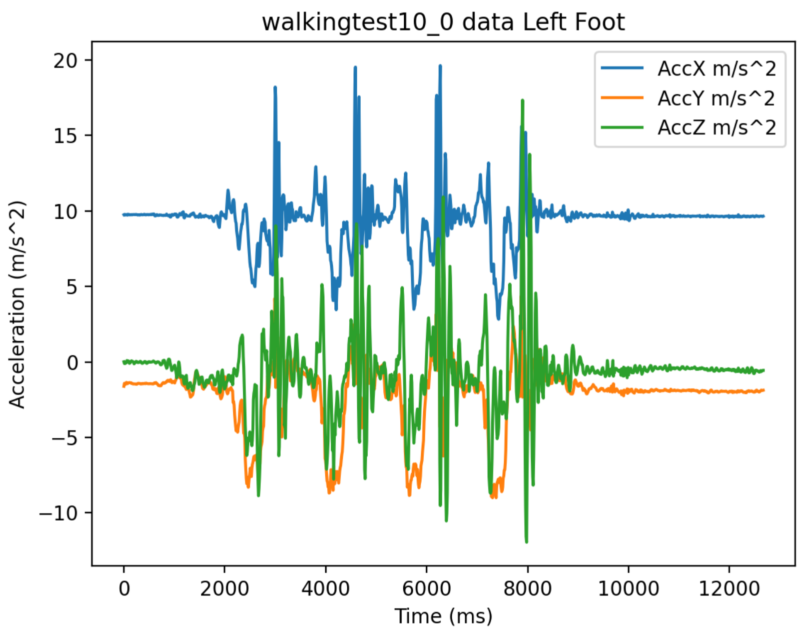

Figure 7.3. Raw IMU Acceleration Data in X, Y and Z directions.

strike event. A period of almost no acceleration (nearly flat graph) is observed after, indicating the mid-stance phase. Reducing acceleration is followed indicating the toe off phase as we had expected. The spikes represent the number of steps taken by the subject. Since the subject is performing the experiment by walking in the global Z-direction, higher acceleration is observed in that direction. Due to the cyclic motion of the foot during the gait cycle, we also observe slight accelerations in the Y and small difts in the X-directions. The raw data, as expected, is heavily noisy. Post processing algorithms using the previously mentioned Madgwick Filter were employed. The Madgwick filter accounts for the IMU accelerometer, gyroscope and magnetometer readings and outputs the relative rotation of the IMU with respect to the global coordinate system. Figure 7.4 shows us the angle by which the IMU accelerometer data needs to be rotated in order to match up with the global coordinates.

We then integrate and obtain the displacement in each direction (Figure 7.5).

As expected, the displacement in the Z-direction is steadily increasing. In the Y-direction, small bumps can be observed. This is due to the cyclic motion of the shank during gait. Very

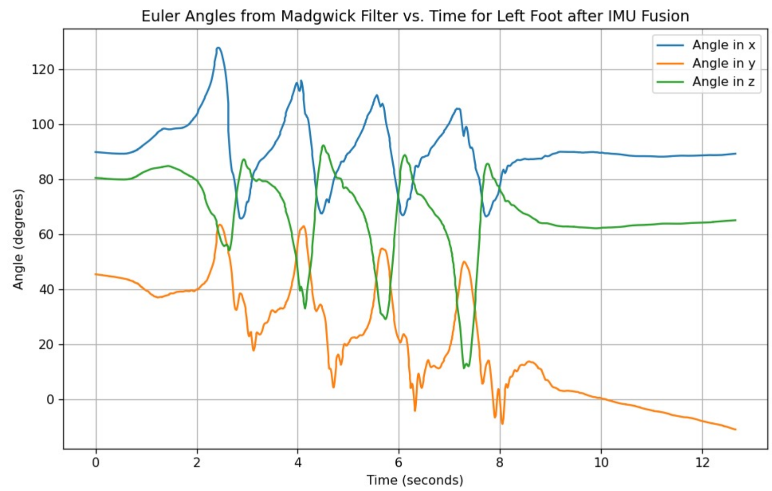

Figure 7.4. IMU orientation with respect to global axes.

Figure 7.5. Displacements in X, Y and Z directions.

slight variations are observed along the X-direction due to small drifts. These displacement values now enable us to obtain other parameters - step length and stride length.

Chapter 8

Discussions

8.1 Gait Parameters Obtained

From the FSR and IMU data, the following gait parameters have been obtained (Refer Table 8.1),

Table 8.1. Summary of Gait Parameters

Gait Parameter	**Value**
Time of stance phase	2s
Time of swing phase	0.5s
Number of steps taken	9
Total time of stride	2.5s
Cadence	216 steps/min [89]
Step Length	0.44m
Stride Length	0.9m

From the FSR readings, it is clear that the time between two consecutive heel strikes will give us the time the foot spent in just the stance phase. Similarly, we can also extract the time the foot spent in the swing phase.

From Figure 7.2, it is apparent that a total of nine steps were taken in this study - four by the left foot and five by the right foot.

The total time of one stride is nothing but the time spent in the swing and stance phases of that one stride. From the previously obtained data, we can conclude that the time of one stride of one foot is 2.5s.

Cadence is defined as the number os steps taken per minute. Since 9 steps were taken in a span of 2.5 seconds, we get a cadence value of 216 steps/min. The normal cadence value range for adults between the ages 20-41 years old is 130-230 steps/min. This indicates a normal gait.

The step length, defined as the distance between two consecutive heel strikes of opposite feet, and the stride length, defined as the distance between two consecutive heel strikes of the same feet, is obtained from the IMU data displacement values.

8.2 Future Scope

For future work on this thesis project, several avenues are proposed to enhance the accuracy and applicability of the current gait analysis methodology. One pivotal strategy involves the implementation of more robust filtering methods, such as Zero Update Velocity, Extended Madgwick Filter, and Extended Kalman Filter. These advanced techniques are crucial for effectively eliminating drifts in IMU readings, thus improving the precision of gait data capture and analysis.

Furthermore, expanding the participant pool is essential. Conducting a study that includes a larger number of healthy individuals alongside amputees will allow for a comprehensive comparison report. This broader data set will provide deeper insights into gait variations and help refine analysis techniques, benefiting both diagnostics and treatment planning.

To further enhance the detail and scope of gait analysis, the inclusion of additional gait parameters—both spatial and kinematic—is suggested. This expansion will allow for a more nuanced understanding of gait mechanics and contribute to more tailored rehabilitation strategies.

Collaboration with prosthetists is also recommended to facilitate a more informed analysis of gait parameters. Such partnerships will bridge the gap between theoretical research and practical implementation, providing critical insights that can lead to improvements in prosthetic design and functionality.

Lastly, there is a significant opportunity to advance the technology by reducing the size of the gait analysis module. Smaller, more compact modules will be less obtrusive for participants, potentially increasing the usability of the system in everyday settings and enhancing the comfort of the users.

Together, these steps will drive forward the capabilities and impact of gait analysis, making it an even more effective tool for clinicians and patients alike.

Bibliography

[1] About Arduino.

[2] D32 — WEMOS documentation.

[3] Force Platform - an overview | ScienceDirect Topics.

[4] Smart Sensor BNO055.

[5] Welcome to Processing!

[6] Gait Analysis After Amputation: Overview, Gait Cycle, Adaptive Strategies of Those Who Have Undergone Amputations. December 2023. Publication: Medscape - eMedicine.

[7] Amjed Al-Fahoum and Momtaz Abadir. Design of a Modified Madgwick Filter for Quaternion-Based Orientation Estimation Using AHRS. 10:174–186, October 2018.

[8] Sushma Alphonsa, Ryan Wuebbles, Takako Jones, Phil Pavilionis, and Nicholas Murray. Spatio-temporal gait differences in facioscapulohumeral muscular dystrophy during single and dual task overground walking - A pilot study. *Journal of Clinical and Translational Research*, 8(2):166–175, March 2022.

[9] Miho Asano, Paula Rushton, William C. Miller, and Barry A. Deathe. Predictors of quality of life among individuals who have a lower limb amputation. *Prosthetics and Orthotics International*, 32(2):231–243, June 2008.

[10] Joonbum Bae and Masayoshi Tomizuka. A tele-monitoring system for gait rehabilitation with an inertial measurement unit and a shoe-type ground reaction force sensor. *Mechatronics*, 23(6):646–651, September 2013.

[11] Richard Baker. Gait analysis methods in rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 3:4, March 2006.

[12] R. Baranek. Inertial Measurement Unit – Data Fusion and Visualization using MATLAB. *IFAC Proceedings Volumes*, 45(7):12–16, January 2012.

[13] Gerasimos Bastas, Joshua J. Fleck, Richard A. Peters, and Karl E. Zelik. IMU-Based Gait Analysis in Lower Limb Prosthesis Users: Comparison of Step Demarcation Algorithms. *Gait & posture*, 64:30–37, July 2018.

[14] Stephanie A. Bridenbaugh and Reto W. Kressig. Laboratory review: the role of gait analysis in seniors' mobility and fall prevention. *Gerontology*, 57(3):256–264, 2011.

[15] M E Busse, C M Wiles, and R W M van Deursen. Community walking activity in neurological disorders with leg weakness. *Journal of Neurology, Neurosurgery, and Psychiatry*, 77(3):359–362, March 2006.

[16] Pei-Hao Chen, Rong-Long Wang, De-Jyun Liou, and Jin-Siang Shaw. Gait Disorders in Parkinson's Disease: Assessment and Management. *International Journal of Gerontology*, 7(4):189–193, December 2013.

[17] Yosra Cherni, Simon Laurendeau, Maxime Robert, and Katia Turcot. The Influence of Transtibial Prosthesis Type on Lower-Body Gait Adaptation: A Case Study. *International Journal of Environmental Research and Public Health*, 20(1):439, December 2022.

[18] Daniel H. K. Chow, Andrew D. Holmes, Christina K. L. Lee, and S. W. Sin. The effect of prosthesis alignment on the symmetry of gait in subjects with unilateral transtibial amputation. *Prosthetics and Orthotics International*, 30(2):114–128, August 2006.

[19] María Coca-Tapia, Alicia Cuesta-Gómez, Francisco Molina-Rueda, and María Carratalá-Tejada. Gait Pattern in People with Multiple Sclerosis: A Systematic Review. *Diagnostics*, 11(4):584, March 2021.

[20] Steffi L. Colyer, Murray Evans, Darren P. Cosker, and Aki I. T. Salo. A Review of the Evolution of Vision-Based Motion Analysis and the Integration of Advanced Computer Vision Methods Towards Developing a Markerless System. *Sports Medicine - Open*, 4(1):24, June 2018.

[21] Tee Connie, Timilehin B. Aderinola, Thian Song Ong, Michael Kah Ong Goh, Bayu Erfianto, and Bedy Purnama. Pose-Based Gait Analysis for Diagnosis of Parkinson's Disease. *Algorithms*, 15(12):474, December 2022. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[22] Michael Conzemius. Limitations of force platform gait analysis.

[23] Antonio I Cuesta-Vargas, Alejandro Galán-Mercant, and Jonathan M Williams. The use of inertial sensors system for human motion analysis. *Physical Therapy Reviews*, 15(6):462–473, December 2010.

[24] Carolin Curtze, Vrutangkumar V. Shah, Alexa M. Stefanko, Marian L. Dale, John G. Nutt, Martina Mancini, and Fay B. Horak. Stride width and postural stability in frontal gait disorders and Parkinson's disease. *Journal of Neurology*, 271(7):3721–3730, July 2024.

[25] Ratan Das, Sudip Paul, Gajendra Kumar Mourya, Neelesh Kumar, and Masaraf Hussain. Recent Trends and Practices Toward Assessment and Rehabilitation of Neurodegenerative Disorders: Insights From Human Gait. *Frontiers in Neuroscience*, 16:859298, April 2022.

[26] Cristiano De Marchis, Simone Ranaldi, Tiwana Varrecchia, Mariano Serrao, Stefano Filippo Castiglia, Antonella Tatarelli, Alberto Ranavolo, Francesco Draicchio, Francesco Lacquaniti, and Silvia Conforto. Characterizing the Gait of People With Different Types of Amputation and Prosthetic Components Through Multimodal Measurements: A Methodological Perspective. *Frontiers in Rehabilitation Sciences*, 3:804746, March 2022.

[27] Luca De Vivo Nicoloso, Joshua Pelz, Herb Barrack, and Falko Kuester. Towards 3D printing of a monocoque transtibial prosthesis using a bio-inspired design workflow. *Rapid Prototyping Journal*, November 2021.

[28] Marcin Derlatka and Marek Parfieniuk. Real-world measurements of ground reaction forces of normal gait of young adults wearing various footwear. *Scientific Data*, 10(1):60, January 2023. Publisher: Nature Publishing Group.

[29] Lazzaro di Biase, Alessandro Di Santo, Maria Letizia Caminiti, Alfredo De Liso, Syed Ahmar Shah, Lorenzo Ricci, and Vincenzo Di Lazzaro. Gait Analysis in Parkinson's Disease: An Overview of the Most Accurate Markers for Diagnosis and Symptoms Monitoring. *Sensors (Basel, Switzerland)*, 20(12):3529, June 2020.

[30] Timothy R. Dillingham, Liliana E. Pezzin, and Ellen J. MacKenzie. Limb amputation and limb deficiency: epidemiology and recent trends in the United States. *Southern Medical Journal*, 95(8):875–883, August 2002.

[31] Timothy R. Dillingham, Liliana E. Pezzin, and Ellen J. Mackenzie. Racial differences in the incidence of limb loss secondary to peripheral vascular disease: a population-based study. *Archives of Physical Medicine and Rehabilitation*, 83(9):1252–1257, September 2002.

[32] L. B. Ebskov. Major amputation for malignant melanoma: an epidemiological study. *Journal of Surgical Oncology*, 52(2):89–91, February 1993.

[33] Elham Esfandiari, Amir Yavari, Amir Karimi, Mehdi Masoumi, Mohammadreza Soroush, and Hassan Saeedi. Long-term symptoms and function after war-related lower limb amputation: A national cross-sectional study. *Acta Orthopaedica et Traumatologica Turcica*, 52(5):348–351, September 2018.

[34] Arezoo Eshraghi, Noor Azuan Abu Osman, Mohammad Karimi, Hossein Gholizadeh, Ehsan Soodmand, and Wan Abu Bakar Wan Abas. Gait Biomechanics of Individuals with Transtibial Amputation: Effect of Suspension System. *PLoS ONE*, 9(5):e96988, May 2014.

[35] Alberto Esquenazi. Gait analysis in lower-limb amputation and prosthetic rehabilitation. *Physical Medicine and Rehabilitation Clinics of North America*, 25(1):153–167, February 2014.

[36] J. Feinglass, J. L. Brown, A. LoSasso, M. W. Sohn, L. M. Manheim, S. J. Shah, and W. H. Pearce. Rates of lower-extremity amputation and arterial reconstruction in the United States, 1979 to 1996. *American Journal of Public Health*, 89(8):1222–1227, August 1999.

[37] Robert Gailey, Kerry Allen, Julie Castles, Jennifer Kucharik, and Mariah Roeder. Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use. *Journal of Rehabilitation Research and Development*, 45(1):15–29, 2008.

[38] Nathaly Gaudreault, Denis Gravel, Sylvie Nadeau, Sylvie Houde, and Denis Gagnon. Gait patterns comparison of children with Duchenne muscular dystrophy to those of control subjects considering the effect of gait velocity. *Gait & Posture*, 32(3):342–347, July 2010.

[39] Uri Givon, Gabriel Zeilig, and Anat Achiron. Gait analysis in multiple sclerosis: characterization of temporal-spatial parameters using GAITRite functional ambulation system. *Gait & Posture*, 29(1):138–142, January 2009.

[40] Giulia Grande, Federico Triolo, Arturo Nuara, Anna-Karin Welmer, Laura Fratiglioni, and Davide L. Vetrano. Measuring gait speed to better identify prodromal dementia. *Experimental Gerontology*, 124:110625, September 2019.

[41] Trupti Gujarathi and Kalyani Bhole. GAIT ANALYSIS USING IMU SENSOR. In *2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, pages 1–5, July 2019.

[42] Yao Guo, Jianxin Yang, Yuxuan Liu, Xun Chen, and Guang-Zhong Yang. Detection and assessment of Parkinson's disease based on gait analysis: A survey. *Frontiers in Aging Neuroscience*, 14, August 2022. Publisher: Frontiers.

[43] D Hazry, M Sofian, and A Zul Azfar. Study of Inertial Measurement Unit Sensor. 2009.

[44] Yi He, Yuxia Chen, Li Tang, Jing Chen, Jing Tang, Xiaoxuan Yang, Songchuan Su, Chen Zhao, and Nong Xiao. Accuracy validation of a wearable IMU-based gait analysis in healthy female. *BMC Sports Science, Medicine and Rehabilitation*, 16(1):2, January 2024.

[45] J. Hebenton, H. Scott, C. Seenan, and F. Davie-Smith. Relationship between models of care and key rehabilitation milestones following unilateral transtibial amputation: a national cross-sectional study. *Physiotherapy*, 105(4):476–482, December 2019.

[46] Koyu Hori, Yufeng Mao, Yumi Ono, Hiroki Ora, Yuki Hirobe, Hiroyuki Sawada, Akira Inaba, Satoshi Orimo, and Yoshihiro Miyake. Inertial Measurement Unit-Based Estimation of Foot Trajectory for Clinical Gait Analysis. *Frontiers in Physiology*, 10, January 2020. Publisher: Frontiers.

[47] Abdul Aziz Hulleck, Dhanya Menoth Mohan, Nada Abdallah, Marwan El Rich, and Kinda Khalaf. Present and future of gait assessment in clinical practice: Towards the application of novel trends and technologies. *Frontiers in Medical Technology*, 4:901331, December 2022.

[48] Tom Ichinohe, Hiromi Takahashi, and Yukihiro Fujita. Force plate analysis of ground reaction forces in relation to gait velocity of healthy Beagles. September 2022. Section: American Journal of Veterinary Research.

[49] Miroslav Janura, Michal Mayer, Iva Dlabolová, Milan Elfmark, and Petra Murcková. APPLICATION OF A 3D VIDEOGRAPHY IN THE ANALYSIS OF GAIT - BASIC INFORMATION. January 1998.

[50] Eun-tae Jeon and Hwi-young Cho. 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, November 2020.

[51] Xiaohong Jia, Shuangfu Suo, Fan Meng, and Rencheng Wang. Effects of alignment on interface pressure for transtibial amputee during walking. *Disability and Rehabilitation. Assistive Technology*, 3(6):339–343, November 2008.

[52] Ashutosh Kharb, Vipin Saini, Y Jain, Surender Dhiman, M Tech, and Scholar. A review of gait cycle and its parameters. *IJCEM Int J Comput Eng Manag*, 13, January 2011.

[53] Maya Kirilova, Alexander Klein, Lars H. Lindner, Silke Nachbichler, Thomas Knösel, Christof Birkenmaier, Andrea Baur-Melnyk, and Hans Roland Dürr. Amputation for Extremity Sarcoma: Indications and Outcomes. *Cancers*, 13(20):5125, October 2021.

[54] L. A. Lavery, H. R. Ashry, W. van Houtum, J. A. Pugh, L. B. Harkless, and S. Basu. Variation in the incidence and proportion of diabetes-related amputations in minorities. *Diabetes Care*, 19(1):48–52, January 1996.

[55] Wenqi Liang, Fanjie Wang, Ao Fan, Wenrui Zhao, Wei Yao, and Pengfei Yang. Extended Application of Inertial Measurement Units in Biomechanics: From Activity Recognition to Force Estimation. *Sensors*, 23(9):4229, January 2023. Number: 9 Publisher: Multidisciplinary Digital Publishing Institute.

[56] Mario Manto, Mariano Serrao, Stefano Filippo Castiglia, Dagmar Timmann, Elinor Tzvi-Minker, Ming-Kai Pan, Sheng-Han Kuo, and Yoshikazu Ugawa. Neurophysiology of cerebellar ataxias and gait disorders. *Clinical Neurophysiology Practice*, 8:143–160, July 2023.

[57] Rachel Mason, Alan Godfrey, Gillian Barry, and Samuel Stuart. Wearables for running gait analysis: A study protocol. *PLOS ONE*, 18(9):e0291289, September 2023.

[58] Theresa E. McGuirk, Elliott S. Perry, Wandasun B. Sihanath, Sherveen Riazati, and Carolynn Patten. Feasibility of Markerless Motion Capture for Three-Dimensional Gait Assessment in Community Settings. *Frontiers in Human Neuroscience*, 16, June 2022. Publisher: Frontiers.

[59] Matko Milovic, Gonzalo Farías, Sebastián Fingerhuth, Francisco Pizarro, Gabriel Hermosilla, and Daniel Yunge. Detection of Human Gait Phases Using Textile Pressure Sensors: A Low Cost and Pervasive Approach. *Sensors*, 22(8):2825, January 2022. Number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

[60] Ralph Jasper Mobbs, Jordan Perring, Suresh Mahendra Raj, Monish Maharaj, Nicole Kah Mun Yoong, Luke Wicent Sy, Rannulu Dineth Fonseka, Pragadesh Natarajan, and Wen Jie Choy. Gait metrics analysis utilizing single-point inertial measurement units: a systematic review. *mHealth*, 8:9, January 2022.

[61] Lindsey K. Molina, Gabriella H. Small, and Richard R. Neptune. The influence of step width on balance control and response strategies during perturbed walking in healthy young adults. *Journal of Biomechanics*, 157:111731, August 2023.

[62] David C. Morgenroth, Alfred C. Gellhorn, and Pradeep Suri. Osteoarthritis in the disabled population: a mechanical perspective. *PM & R: the journal of injury, function, and rehabilitation*, 4(5 Suppl):S20–27, May 2012.

[63] Matteo Moro, Giorgia Marchesi, Filip Hesse, Francesca Odone, and Maura Casadio. Markerless vs. Marker-Based Gait Analysis: A Proof of Concept Study. *Sensors (Basel, Switzerland)*, 22(5):2011, March 2022.

[64] Alvaro Muro-de-la Herran, Begonya Garcia-Zapirain, and Amaia Mendez-Zorrilla. Gait Analysis Methods: An Overview of Wearable and Non-Wearable Systems, Highlighting Clinical Applications. *Sensors (Basel, Switzerland)*, 14(2):3362–3394, February 2014.

[65] Lars Mündermann, Stefano Corazza, and Thomas P Andriacchi. The evolution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications. *Journal of NeuroEngineering and Rehabilitation*, 3:6, March 2006.

[66] Heidi Nadollek, Sandra Brauer, and Rosemary Isles. Outcomes after trans-tibial amputation: the relationship between quiet stance ability, strength of hip abductor muscles and gait. *Physiotherapy Research International: The Journal for Researchers and Clinicians in Physical Therapy*, 7(4):203–214, 2002.

[67] Tommy Oberg, Alek Karsznia, and Kurt Oberg. Basic gait parameters : Reference data for normal subjects, 10-79 years of age. 1993.

[68] Bernard O'Keeffe and Shraddha Rout. Prosthetic Rehabilitation in the Lower Limb. *Indian Journal of Plastic Surgery : Official Publication of the Association of Plastic Surgeons of India*, 52(1):134–143, January 2019.

[69] Muyinat Y. Osoba, Ashwini K. Rao, Sunil K. Agrawal, and Anil K. Lalwani. Balance and gait in the elderly: A contemporary review. *Laryngoscope Investigative Otolaryngology*, 4(1):143–153, February 2019.

[70] Megumi Ota, Hiroshige Tateuchi, Takaya Hashiguchi, and Noriaki Ichihashi. Verification of validity of gait analysis systems during treadmill walking and running using human pose tracking algorithm. *Gait & Posture*, 85:290–297, March 2021.

[71] Purnima Padmanabhan, Keerthana Sreekanth Rao, Shivam Gulhar, Kendra M. Cherry-Allen, Kristan A. Leech, and Ryan T. Roemmich. Persons post-stroke improve step length symmetry by walking asymmetrically. *Journal of Neuroengineering and Rehabilitation*, 17(1):105, August 2020.

[72] Mark R. Pitkin. Effects of Design Variants in Lower-Limb Prostheses on Gait Synergy. *Journal of prosthetics and orthotics : JPO*, 9(3):113–122, 1997.

[73] S. Portnoy, Z. Yizhar, N. Shabshin, Y. Itzchak, A. Kristal, Y. Dotan-Marom, I. Siev-Ner, and A. Gefen. Internal mechanical conditions in the soft tissues of a residual limb of a trans-tibial amputee. *Journal of Biomechanics*, 41(9):1897–1909, 2008.

[74] J. S. Rietman, K. Postema, and J. H. B. Geertzen. Gait analysis in prosthetics: opinions, ideas and conclusions. *Prosthetics and Orthotics International*, 26(1):50–57, April 2002.

[75] Martina Rinaldi, Maurizio Petrarca, Alberto Romano, Gessica Vasco, Carmen D'Anna, Daniele Bibbo, Maurizio Schmid, Enrico Castelli, and Silvia Conforto. Progression of muscular co-activation and gait variability in children with Duchenne muscular dystrophy: A 2-year follow-up study. *Clinical Biomechanics*, 78, August 2020. Publisher: Elsevier.

[76] Kristóf Rácz and Rita M. Kiss. Marker displacement data filtering in gait analysis: A technical note. *Biomedical Signal Processing and Control*, 70:102974, September 2021.

[77] Sofia Scataglini, Eveline Abts, Cas Van Bocxlaer, Maxime Van den Bussche, Sara Meletani, and Steven Truijen. Accuracy, Validity, and Reliability of Markerless Camera-Based 3D Motion Capture Systems versus Marker-Based 3D Motion Capture Systems in Gait Analysis: A Systematic Review and Meta-Analysis. *Sensors*, 24(11):3686, January 2024. Number: 11 Publisher: Multidisciplinary Digital Publishing Institute.

[78] Karin Schmid-Zalaudek, Theresa Fischer, Zoltán Száva, Helmut Karl Lackner, Ursula Kropiunig, Christian Bittner, Karl Höcker, Günther Winkler, and Gerfried Peternell. Kinetic Gait Parameters in Unilateral Lower Limb Amputations and Normal Gait in Able-Bodied: Reference Values for Clinical Application. *Journal of Clinical Medicine*, 11(10):2683, May 2022.

[79] Céline Schreiber and Florent Moissenet. A multimodal dataset of human gait at different walking speeds established on injury-free adult participants. *Scientific Data*, 6(1):111, July 2019. Publisher: Nature Publishing Group.

[80] Isabella Schwartz, Yonah Ofran, Naama Karniel, Martin Seyres, and Sigal Portnoy. Step Length Asymmetry Predicts Rehabilitation Length in Subacute Post Stroke Patients. *Symmetry*, 14(10):1995, October 2022. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

[81] Ruud Selles, Johannes Bussmann, A. J. Knoek Van Soest, and Henk Stam. The effect of prosthetic mass properties on the gait of transtibial amputees–a mathematical model. *Disability and Rehabilitation*, 26(12):694–704, June 2004.

[82] Dimple Sethi, Sourabh Bharti, and Chandra Prakash. A comprehensive survey on gait analysis: History, parameters, approaches, pose estimation, and future work. *Artificial Intelligence in Medicine*, 129:102314, July 2022.

[83] Camille J. Shanahan, Frederique M. C. Boonstra, L. Eduardo Cofré Lizama, Myrte Strik, Bradford A. Moffat, Fary Khan, Trevor J. Kilpatrick, Anneke van der Walt, Mary P. Galea, and Scott C. Kolbe. Technologies for Advanced Gait and Balance Assessments in People with Multiple Sclerosis. *Frontiers in Neurology*, 8, February 2018. Publisher: Frontiers.

[84] Sheldon R. Simon. Quantification of human motion: gait analysis—benefits and limitations to its application to clinical problems. *Journal of Biomechanics*, 37(12):1869–1880, December 2004.

[85] Tina Smith and Massimiliano Ditroilo. Force plate coverings significantly affect measurement of ground reaction forces. *PLOS ONE*, 18(11):e0293959, November 2023.

[86] Jan Stenum, Melody M. Hsu, Alexander Y. Pantelyat, and Ryan T. Roemmich. Clinical gait analysis using video-based pose estimation: Multiple perspectives, clinical populations, and measuring change. *PLOS Digital Health*, 3(3):e0000467, March 2024.

[87] Weijun Tao, Tao Liu, Rencheng Zheng, and Hutian Feng. Gait Analysis Using Wearable Sensors. *Sensors (Basel, Switzerland)*, 12(2):2255–2283, February 2012.

[88] Daniela TarniŢă. Wearable sensors used for human gait analysis. *Romanian Journal of Morphology and Embryology = Revue Roumaine De Morphologie Et Embryologie*, 57(2):373–382, 2016.

[89] Catrine Tudor-Locke, Scott W. Ducharme, Elroy J. Aguiar, John M. Schuna, Tiago V. Barreira, Christopher C. Moore, Colleen J. Chase, Zachary R. Gould, Marcos A. Amalbert-Birriel, Jose Mora-Gonzalez, Stuart R. Chipkin, and John Staudenmayer. Walking cadence (steps/min) and intensity in 41 to 60-year-old adults: the CADENCE-adults study. *International Journal of Behavioral Nutrition and Physical Activity*, 17(1):137, November 2020.

[90] Frantisek Vaverka, Milan Elfmark, Zdenek Svoboda, and Miroslav Janura. System of gait analysis based on ground reaction force assessment. *Acta Gymnica*, 45, September 2015.

[91] Ericka P. von Kaeppler, Alexander Hetherington, Claire A. Donnelley, Syed H. Ali, Corin Shirley, Sravya T. Challa, Emily Lutyens, Billy T. Haonga, Saam Morshed, Jan Andrysek, and David W. Shearer. Impact of prostheses on quality of life and functional status of transfemoral amputees in Tanzania. *African Journal of Disability*, 10:839, September 2021.

[92] David Sing Yee Vun, Robert Bowers, and Anthony McGarry. Vision-based motion capture for the gait analysis of neurodegenerative diseases: A review. *Gait & Posture*, 112:95–107, July 2024.

[93] Logan Wade, Laurie Needham, Polly McGuigan, and James Bilzon. Applications and limitations of current markerless motion capture methods for clinical gait biomechanics. *PeerJ*, 10:e12995, February 2022.

[94] Yufridin Wahab and Norantanum Abu Bakar. Gait analysis measurement for sport application based on ultrasonic system. In *2011 IEEE 15th International Symposium on Consumer Electronics (ISCE)*, pages 20–24, June 2011. ISSN: 2159-1423.

[95] S Wardoyo, P T Hutajulu, and O Togibasa. A Development of Force Plate for Biomechanics Analysis of Standing and Walking. *Journal of Physics: Conference Series*, 739:012118, August 2016.

[96] J. S. Wrobel, J. A. Mayfield, and G. E. Reiber. Geographic variation of lower-extremity major amputation in individuals with and without diabetes in the Medicare population. *Diabetes Care*, 24(5):860–864, May 2001.

[97] Dong Hyun Yoon, Jeong-Hyun Kim, Kyuwon Lee, Jae-Sung Cho, Seong-Ho Jang, and Shi-Uk Lee. Inertial measurement unit sensor-based gait analysis in adults and older adults: A cross-sectional study. *Gait & Posture*, 107:212–217, January 2024.

[98] Riky Tri Yunardi, Tri Arief Sardjono, and Ronny Mardiyanto. Motion Capture System based on RGB Camera for Human Walking Recognition using Marker-based and Markerless for Kinematics of Gait. In *2023 IEEE 13th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, pages 262–267, May 2023. ISSN: 2836-4317.

[99] Runting Zhong and Pei-Luen Patrick Rau. A Mobile Phone–Based Gait Assessment App for the Elderly: Development and Evaluation. *JMIR mHealth and uHealth*, 8(5):e14453, May 2020.

[100] Kathryn Ziegler-Graham, Ellen J. MacKenzie, Patti L. Ephraim, Thomas G. Travison, and Ron Brookmeyer. Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050. *Archives of Physical Medicine and Rehabilitation*, 89(3):422–429, March 2008.

[101] Özlem Ülger, Tezel Yıldırım Şahan, and Seher Erol Çelik. A systematic literature review of physiotherapy and rehabilitation approaches to lower-limb amputation. *Physiotherapy Theory and Practice*, 34(11):821–834, November 2018.