Master's Thesis

GaitScanner: The design and development of a novel autonomous, portable, subject-centred robotic system for video data acquisition of human walking gait

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Declaration of Authorship

I, Daniel Thomas, declare that this thesis titled, 'GaitScanner: The design and development of a novel autonomous, portable, subject-centred robotic system for video data acquisition of human walking gait' and the work presented in it are my own. I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Date: 16/01/2017

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Abstract

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Master of Engineering (Biomedical)

GaitScanner: The design and development of a novel autonomous, portable, subject-centred robotic system for video data acquisition of human walking gait

by Daniel Thomas

Human gait is a commonly studied area of the human body and has been of major interest to both researchers and clinicians. Gait patterns have been used to help with the diagnosis of different disorders and conditions. Gait is typically analysed using observational analysis and a combination of the following techniques: temporal & spatial analysis, kinetic analysis, dynamic electromyography and kinematics analysis. While conventional gait analysis methods that combine the aforementioned techniques are more than capable of producing exceptional results they are also very expensive, such that they are only available in a limited number of facilities, making it difficult for patients to readily access this technology. They also require a closed/limited workspace and are relatively complex to operate such that it requires a user to undertake comprehensive training. Additionally, clinicians often schedule consultations as short as 20 minutes however, in some instances the setup for kinematic analysis can exceed this time and as a result this technology can be inconvenient to use in a clinical environment.

The GaitScanner project, which involves the development of a portable video gait analysis device, focuses on the design and developmental process for a functioning video observational gait analysis robot prototype expanding on the ideas and vision for the project that began last year. It is envisaged that the device will provide clinicians with a novel method for recording gait in high definition video using a portable and autonomous system that will follow a patient while not impeding movement. The recorded footage can then be accessed for further analysis or stored for patient monitoring.

From the project requirements and after reviewing the relevant literature, the main deliverables can be broken down to 3 key areas: an enclosure to protect and cover any electronic componentry, a video playback GUI to assist in the post processing of recorded footage and an optimised control system that reduces the resultant delay of the system upon acceleration and deceleration of the device. The design process for the enclosure involved an ideation phase consisting of the initial planning for the design. The ideation phase was followed by three separate design stages with each subsequent design improving on the last. Finally, the prototype development phase is introduced, which involved the actual construction of the GaitScanner.

In its current state the clinician etc. does not have a dedicated playback program to view the video footage, as such the project also involved the production a playback GUI. Once the video files have been transferred to a computer they can be selected by the program and which is displayed side by side and has the ability to be controlled simultaneously. The program also has options for inputting notes regarding the patient which can then be exported as a txt file.

Keywords: gait; observational; analysis; assessment; rehabilitation; autonomous; robot; video

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Abbreviations

OGA	**O**bservational **G**ait **A**nalysis
VOGA	**V**ideo **O**bservational **G**ait **A**nalysis
CAD	**C**omputer-**A**ided **D**esign
IR	**I**nfra-**R**ed
PID	**P**roportional **I**ntegral **D**ifferential
GUI	**G**raphic **U**ser **I**nterface

Subject / Patient	Person subjected or to be subjected to clinical gait assessment
Client	Industry-based partner

1.

Introduction

1.1 What is Gait?

For many centuries human locomotion has been a major interest to scientists, however, it was not until more recent times (circa the 19th century) that this could be recorded. The term gait is used as the biometric for walking. Since the creation of cameras, technology has provided an accessible means of truly developing our understanding of how humans walk, notably through work by Braune and Fischer (Braune & Fischer 1895). Studies regarding gait have progressed the understanding of walking from the physiological aspects of bones, ligaments and the activation of muscles etc. to more specific techniques and patterns which have led to the discoveries of new rehabilitation methods and the categorisation of various walking impairments. Before gait can be analysed the basic concepts namely the gait cycle and basic parameters must be introduced.

1.1.1 A Conventional Gait Cycle

The most basic gait motion can be defined by simple straight line walking; this motion can be divided into separate phases that form a single gait cycle, Figure 1.1. The cycle is initiated by the right foot heel strike, also known as the **initial contact** and is closely followed by the **loading response** phase, which is represented by flat right foot support. During the **mid-stance** phase both the hamstring and quadriceps contract in order for the right leg to support the newly applied load (as the left leg enters the mid-swing phase). The **terminal stance** occurs when the heel is lifted prior to the **pre-swing** or toe-off phase. Once the pre-swing has been initiated the remaining 40% of the gait cycle is encompassed by the **initial**, **mid** and **terminal swing** whereby the right leg begins the swing with a propulsion from the toe-off and then continues to rotate at the hip joint before finishing with a right foot heel strike, returning to the beginning of the gait cycle.

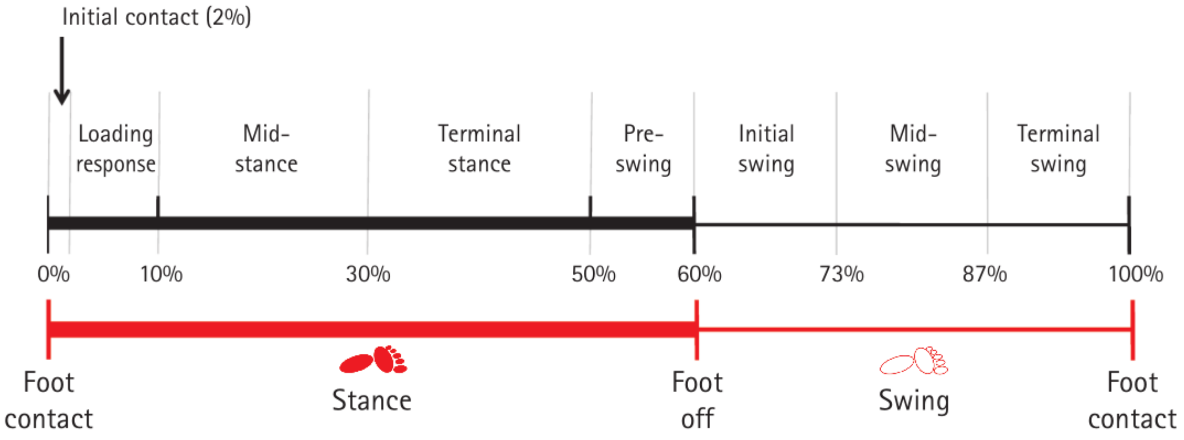

Figure 1.1: Phases of the gait cycle.

1.1.2 Basic Measurements

The fundamental purpose of gait analysis to determine the overall locomotor function of a subject. This is accomplished by comparing and contrasting different gait parameters against expected values. Modern advancements in technology have allowed clinicians to record a variety of different parameters using the many tools at their disposal. However, gait function can still be evaluated using only the most elementary parameters, namely the spatial and temporal parameters.

1.1.2.1 Spatial Parameters

Step/Stride Length

Step length is the distance one part of a foot travels away from the opposite foot. Typically, the step length is measured from either the heel contact or toe-off point of a step cycle. Furthermore, stride length can be described as the distance between the successive points of the same foot. For conventional gait cycles the stride length or step lengths for both feet are approximately equal (75-80 cm), this is referred to a symmetric gait pattern. As a result, clinicians will often observe for any asymmetric gait patters, as represented in Figure 1.2.

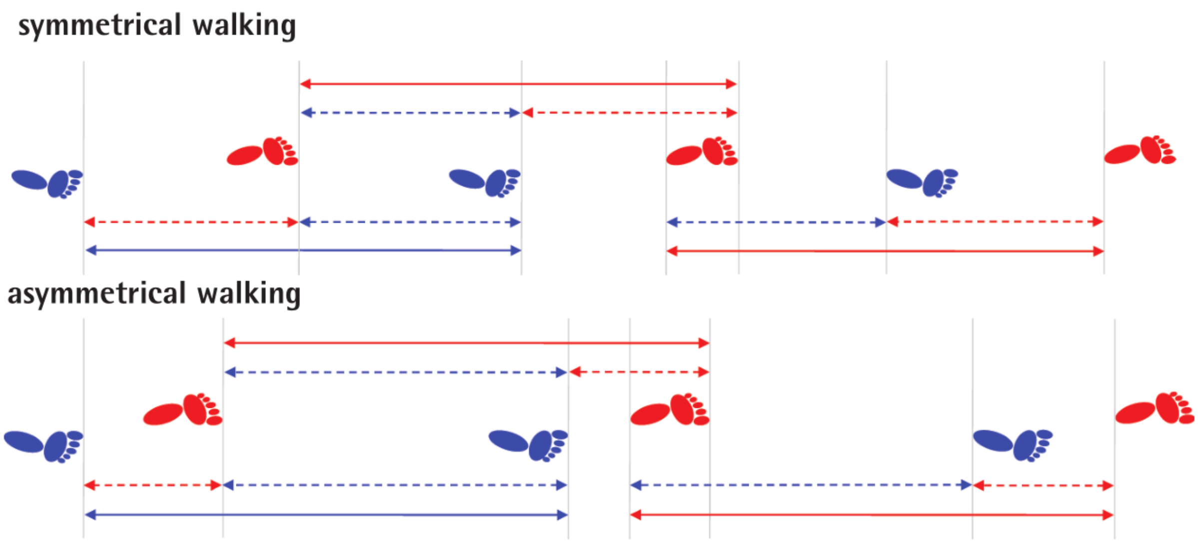

Figure 1.2: Symmetrical vs. asymmetrical step/stride length walking pattern.

Step Width

Step width is the separation distance between both feet in the mediolateral direction and is most commonly measured from the centre point of the heel. Normal step widths range between 8-10 cm and is seen to affect walking stability if varied greatly.

1.1.2.2 Temporal Parameters

Cadence/Step Rate & Step/Stride Time

Cadence is the total number of steps taken in one minute, also known as the step rate. This is closely related to the step/stride time, which can be described as the duration to complete one step/stride cycle respectively.

1.1.2.3 Spatio-temporal Parameter

Walking Speed

Combining both spatial and temporal measurements yields walking speed. Walking speed is directly related to the step rate and step length:

$$Walking\ speed\ (m/s) = \frac{Step\ rate \times step\ length}{60}$$

1.2 Project Overview

This project aims to focus on the design and developmental process for a functioning VOGA robot prototype. It is envisaged that the device will provide clinicians with a novel method for recording gait in high definition, using a portable and autonomous system that will follow a patient while not impeding movement. The recorded footage can then be accessed for further analysis or stored for patient monitoring. The device has been titled the **GaitScanner**; an acronym for **G**ait **S**ubject-**C**entred **A**utonomous **N**ear-**N**ative **E**nvironment **R**ecorder. While portable gait analysis devices currently exist, the GaitScanner will surpass the capabilities of these devices by offering a non-wearable system suitable for operation in locations outside of a specialist environment, such as care homes or hospital facilities.

1.2.1 Project Motivation

The primary motivation behind this project originated from the client and his desire to develop a clinical device capable of performing autonomous video gait analysis to assist clinicians with the monitoring and diagnosis of a subjects' condition. The client initially pitched this project idea to the Flinders Medical Devices Partnering Program but was ultimately rejected. However, rather than shutting down the project completely, it was restructured to become a final year Masters project in 2015. After 12 months of development, a proof of concept prototype model was made. The project was offered again in 2016 to be undertaken as a final year Masters project, with the goal of further developing the prototype into a clinically viable device.

1.2.2 Project Objective

The primary outcome for the project is to have a clinically ready device, such that the client can immediately begin clinical evaluation. While the success of the project will be heavily determined by the final product, the functionality of the device will be evaluated against the requirements and specifications defined in conjunction with the client.

1.3 Outline of Thesis

The project followed an iterative design and development process, this thesis outlines the process in a chronological order. Beginning at **Chapter 1**, the basic concepts of gait have been introduced, the motivation for the project was addressed and an overview has been disclosed to the reader. The introduction is followed by a thorough review on the relevant literature relating to gait analysis. The importance of gait analysis is discussed, the different qualitative and quantitative analysis techniques were highlighted, a patent search was conducted and the potential market space that the project could fulfil was identified throughout **Chapter 2**. **Chapter 3** lists the client requirements for the project and further expands them to form engineering specifications. The requirements and specifications are then used to divide the project into three primary components and are adapted to form the initial concepts detailed in **Chapter 4**. The chapter details the conceptualisation process taken to develop each of the components of the project. **Chapter 5** takes all of the ideas from the conceptualisation process and begins to realise them in the development of a prototype. In addition to the development and construction of the prototype, the chapter describes the drive system and video playback GUI design. A user manual that explains how to operate the GaitScanner in its entirety is in **Chapter 6**. **Chapter 7** reflects on the project providing a comparison of the GaitScanner performance against the requirements identified at the beginning of the project. **Chapter 8** concludes the thesis by summarising the post-project work and identifying any areas for future improvement.

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2.

Literature Review

2.1 Introduction

The study of human physiology has been of major importance in the field of medicine. A significant impact toward improving the quality of life for those whom may be living with a physical impairment is being made through modern advancements in clinical technology. Rehabilitation is just one discipline that has benefited greatly, clinicians are now better equipped with the means to assess patients, monitor and follow progress of treatments and diagnose conditions with increased accuracy and with less invasive techniques.

Gait analysis is one common rehabilitation practice conducted primarily for assessing a patients' lower limb functionality. The analysis of walking patterns allows clinicians to identify any abnormal characteristics caused by a specific condition, disease, disorder or as a result of ageing. It is not limited to use as a diagnostic tool however, but also a way to examine the progress of rehabilitation.

For example, gait disorders are heavily correlated to the severity of cognitive decline with healthy elderly patients showing a smaller reduction in physical motor locomotion compared to dementia and early onset dementia sufferers (Beauchet et al. 2008). Hence, gait assessment is regarded as an important tool for the early diagnosis of diseases and syndromes in the elderly. However, gait laboratories are not often available and can be difficult for the elderly or impaired patients to access. The conditions in standard gait laboratories have also been questioned whether the artificial environment has an unconscious effect on a patients’ gait patterns (Coutts 1999). This has encouraged new and innovative gait analysis techniques to be developed that can be conducted outside of a laboratory environment.

From complex quantitative measurements to simpler qualitative notes there are several different means to assess gait, which are discussed throughout this chapter.

2.2 Importance of Gait Analysis

As discussed in the previous chapter gait analysis is used to characterise human locomotion such that different conditions and/or disorders can be identified. The diagnosis of neurological disorders via from gait analysis allows comparisons and measurements of key characteristics such as gait speed, step length, step length symmetry, cadence and support duration (Coutts 1999; Eastlack et al. 1991). Clinicians also use it for monitoring and examining the effectiveness of a particular walking aid or prostheses (Eastlack et al. 1991). Its use is not limited to a clinical environment however, sports biomechanics is gaining interest among athletes and sports players. Athletes are incorporating gait analysis as a part of training to identify any posture related injuries and to maximise running efficiency (Bartlett 2007). Due to advancements in modern technology and demand for security, one novel use of gait analysis is in the field of forensic medicine. Applying biomechanical knowledge to analyse the gait of a perpetrator on surveillance video footage and comparing gait patterns to a suspect can be used a valuable tool towards positive identification (Larsen et al. 2008).

2.3 Gait Analysis Techniques

Human gait is analysed by monitoring different characteristics of walking patterns (Moissenet & Armand 2015) and gait can be examined in a clinical setting using one of two techniques: qualitative analysis or quantitative analysis. Qualitative analysis allows for a patient assessment to be completed without or with minimal equipment in a short time frame. As a result, this is the most common gait analysis method in clinical practice. Quantitative analysis involves the calculation of spatiotemporal parameters to provide clinicians with numerical information regarding a patients' gait (Moissenet & Armand 2015). Typically, the information consists of joint kinematics, kinetics and dynamic EMG data which is recorded using position cameras, foot force sensors and muscle sensors, respectively. The data is then interpreted and used to assist in the clinical assessment of a patient.

2.3.1 Qualitative Gait Analysis

Qualitative analysis is the most common form of gait assessment used by clinicians as it allows for rapid evaluation of a patient's gait using minimal equipment with acceptable results. Due to its simplicity these qualitative methods are often used prior to any quantitative analysis. The primary methods used for qualitative gait analysis can be separated into two categories: self-reported analysis and observational analysis (with the option of video observational analysis).

2.3.1.1 Self-reported Analysis

Self-reporting of walking is the most primitive form of assessment. It is typically brought upon by the loss or impediment of gait function after an individual is subject to an injury or a fall, resulting in pain or discomfort during walking. Self-assessment provides clinicians with a rapid means of obtaining an initial overview of the situation to allow for immediate treatment or care.

Clinicians often use questionnaires to categorise and rank the severity of a patients' initial self-report (Steadman et al. 1997) (an example of a OGA assessment for can be found in Appendix A). The questionnaires can be self-reported or reported by a third party (family members, carers, etc.) depending on the cognitive capability of the patient. They are then evaluated and compared to the International Classification of Functioning, Disability and Health (ICF), which is represented in Figure 1. The questions can be either global, such that they address gait as one task as a whole, assessing the life participation through perceived performance of daily activities, or local, with specified analysis of gait ability, focusing on specific body function in the activity domain of the ICF (Schwarzkopf et al. 2010). The results of a self-reported analysis are subjective to the both patients and clinicians, as a result it is ideal that the questionnaire is constructed to be independent of age and type of disorder. Consequently, self-reported analysis is almost always followed by Observational Gait Analysis (OGA) and possibly quantitative assessment depending on the situation.

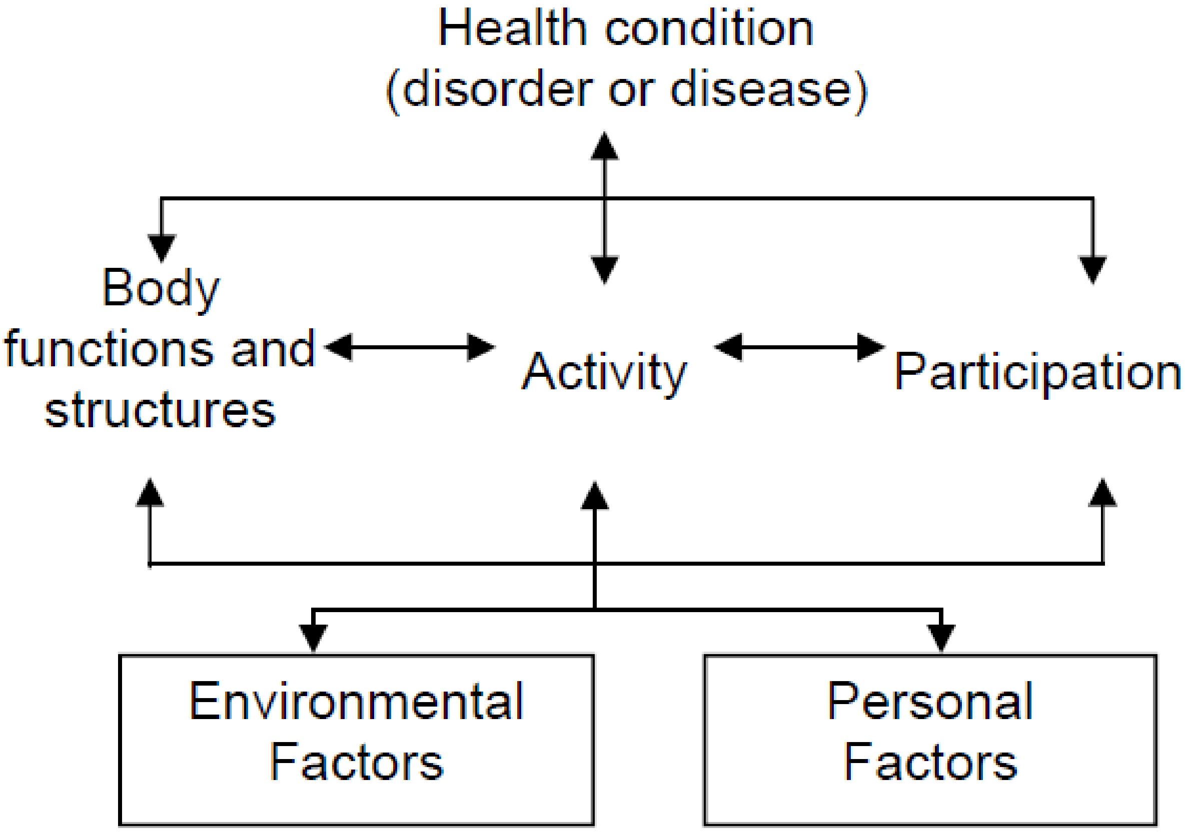


Figure 2.1: International Classification of Functioning, Disability and Health framework (Schwarzkopf et al. 2010)

Currently in environments outside of a clinic, post treatment observational gait analysis (OGA) is particularly important. This method allows for patients to provide the clinician with direct feedback otherwise unattainable from the other analysis techniques, such as primary patient feedback. While this is a viable technique for monitoring patient gait outside of a laboratory, it does question whether a more advanced portable alternative system can be used.

2.3.1.2 Observational Gait Analysis

Following the self-reported analysis clinicians will continue to analyse gait, where the simplest and common form of gait analysis is OGA. While the use of three-dimensional computer assisted gait analysis techniques are most desired, this application is complex, time-consuming and requires highly trained clinicians (Toro et al. 2003). As a result, it is OGA that continues to be the most common method for gait analysis in a clinical environment. OGA does not require any particular equipment and can be performed by both the patient and clinician with minimal instruction and guidance respectively.

During OGA, a clinician visually assesses a patient walking a predetermined route in real-time. The clinician will analyse the patients' gait from coronal (frontal) and sagittal (side) viewpoints, typically focussing on kinematic joint displacement and temporo-spatial factor analysis (Eastlack et al. 1991). The analysis of joints in these planes allows for the assessment of ankle, knee, hip functions. The primary features that are evaluated by the clinician are extensions of the knee during terminal swing, peak hip extensions, trunk and pelvic rotations, balance and stability, foot placement, step length asymmetry and weight transfer during heel strike and toe off (Moissenet & Armand 2015).

Generally, clinicians make diagnostic decisions from OGA using one of four techniques (Kirtley 2006).

1. Pattern recognition – the most common technique used by 68% of clinicians due to the simplicity and fast nature, is a method where a patients' movement is compared to similar gait patterns conditions recalled from previous experiences.
2. Hypothetico-deductive – this reverse method is most common among beginner clinicians as they have less experience to aid with pattern recognition. A hypothesis is created and tested to be either confirmed or disproved.
3. Multiple branching – this is an expansion of the hypothetico-deductive method, where a new hypothesis is created if the original hypothesis is rejected, which continues in an iterative cycle.
4. Exhaustive – is the systematic evaluation of the motion of all body segments, as it looks at all individual components it can be very time-consuming and as a result is the least employed strategy.

Despite the fact OGA is the most common gait analysis technique, its reliability and validity are often questioned when compared to the quantitative gait analysis methods due to the subjective nature and the absence of universal protocols to ensure consistency across the varying clinician skill levels. The primary limiting factors of OGA can be related to time-constraints and the volume of information that can be processed (Baker 2006). While traditional OGA protocols are shown to recommend the exhaustive method with the analysis of 30 or more variables, it was postulated that most clinicians are only able to consider approximately six different gait variables in an average consultation session (Embrey et al. 1990). He also found that 85% of clinicians spend most of their analysis looking at the coronal plane even though most gait features are better observed from the sagittal plane view. In most cases this can be attributed to the fact that OGA is often performed in narrow corridors or small rooms which have inadequate conditions for sagittal plane analysis.

There are observation-based forms that are designed to help clinicians with the evaluation of patient gait through a scaling system that classifies the patient into a predefined group based on the scores of the (Moissenet & Armand 2015). The OGA forms predominantly analyse gait patterns by isolating joints and segments from one another. However, many clinicians prefer to use pattern recognition using the whole body or multiple segments to perform the analysis (Shumway-Cook & Woollacott 2007). Consequently, research identified that not many clinicians are adopting OGA forms to assist in the clinical analysis of gait (Toro et al. 2003). In addition to the OGA forms there are a few standardised tests which allow for an easier method of comparison between sessions. The 4 most common clinical tests are (Steffen et al. 2002):

1. 2-6 min walk test (2MWT/6MWT) – The patient walks for a predefined time usually between 2 to 6 minutes depending of the capability of the patient. This test allows the clinician to assess the level of endurance/fatigue in the patient’s gait characteristics.
2. Timed up & go test (TUG) – The TUG test begins in a seated position and measures the time taken for a patient to stand up, walk 3m, turn around and walk back to the chair before sitting back down.
3. Timed 25-foot walk (T25FW) – The T25FW test records the time taken to walk 25 feet in a straight line.
4. Comfortable and fast gait speeds (CGS and FGS) – This is another short distance test measuring the subject ability to change speed above and below the average walking speed. It is designed to replicate real world situations/tasks such as crossing a road.

2.3.1.3 Videotaped Observational Gait Analysis

To combat the issues regarding real-time OGA, the use of videotaping technology has been introduced as a complementary tool to assist clinicians with gait analysis. Videotaped observational gait analysis (VOGA) is useful for clinicians as it allows for trials to be replayed and paused for frame-by-frame analysis and slowed down, which is believed to improve the overall reliability of assessment. In addition to the playback control options, VOGA is also beneficial to the patient. It reduces the need for numerous repetitions of trials, consequently minimising patient fatigue (Nagano et al. 2014).

VOGA is typically conducted with a camera placed at both the coronal and sagittal views according to the designated walking path. The major limitations using this configuration is that the video footage captured does not maintain a uniform distance from the patient due to the static nature of the cameras. In the coronal plane the patient will be either walking away or towards the camera such that the level of detail will either decrease or increase depending on the direction of motion, a phenomenon commonly referred to as pixilation distortion or fish eye. This can be overcome by adjusting the zoom of the camera to maintain a proportionate distance between the patient, however an automated system of this kind would be expensive and difficult to implement. The sagittal plane would also experience uniformity errors as the patient travels from one side of the frame to the other. Since the camera is not parallel to the patient at all times there will be either a parallax error towards the edge of the frame for fixed rotation cameras or a non-uniform angle rotating camera. Recently rail mounted cameras have been used to address the issues in the sagittal plane (Janshen 2008). However, these systems are very expensive and require specialised rooms to facilitate the equipment. A cheaper alternative to the rail mounted camera system is with use of a treadmill and much like the conventional method the cameras are setup in the coronal and sagittal plane views (Alton et al. 1998). While the assessment of gait can be performed in an area with limited space, the presence of the treadmill does not provide an accurate indication of patient gait. This can be attributed to treadmill instigating the gait motion rather than natural initiation by the subject. Furthermore, the presence of video cameras can cause patients to become subconsciously aware, resulting in unintentional alterations to gait patterns to try and please the clinician (Coutts 1999). For these reasons it is important that the testing conditions are monitored to avoid distractions and replicate an everyday environment. An ideal testing environment should have minimal distractions (including equipment, mirrors or people), be quiet, and have appropriate lighting. There should be at least 10 m of walking space with adequate room at either side of the walk zone for the clinician and any cameras should be setup discretely out of the patients’ field of view (Robinson & Smidt 1981).

Does VOGA have a positive impact on the interrater reliability? This question is often at the centre of studies surrounding the validity of gait analysis techniques. The interrater reliability is compared by using a weighted Kappa coefficient value. In 1985 Krebs studied the interrater reliability of VOGA between 3 trained clinicians of 15 children with lower-limb disabilities (Krebs et al. 1985). He found the total agreement between the clinicians was 67.5% and this test did not utilise slow motion or freeze frame video. Hughes and Bell (1994) developed a standardised form to help 3 clinicians with the analysis of 6 post stroke patients (McGinley et al. 2003). The interrater reliability was only statistically significant during the swing phase and not during the stance phase or overall characterisation of gait. In general, studies have concluded that the reliability of VOGA ranges from moderate to moderate-good. Despite these results, it remains unquestionable that the inclusion of video to OGA assists clinicians and improves the overall reliability of gait assessment.

2.3.2 Quantitative Gait Analysis

Due to the forever evolving field of technology, the capabilities of equipment such as computers, cameras and sensors are increasing our ability to procure and study gait analysis data. Clinicians are now better equipped with numerous tools and advanced systems at their disposal for highly accurate quantitative assessments of human gait. The currently available quantitative gait analysis techniques are typically classified into wearable and non-wearable analysis systems. While these systems all provide clinicians with vital information regarding patient gait, many of these systems measure different gait parameters and have varying methods of operation.

The following subsection details a selection of the most common quantitative systems used by clinicians for gait analysis.

2.3.2.1 Floor Sensor Analysis Systems

Floor systems operate using sensors which are either embedded or placed into the floor and measure gait when a patient walks across the sensor. Floor sensors can either measure force or pressure and come in the form of ground reaction force plates and plantar pressure mats respectively.

Ground Reaction Force Plates

During gait, a ground reaction force (GRF) is generated by the foot upon contact with the ground. A GRF is an equal but opposing force to the force applied by the foot to the ground, due to Newton's 3rd Law of Motion (Muro-de-la-Herran et al. 2014). Using this theory for the basis of its operation, GRF plates can measure the reaction force at specific instances of the gait cycle. In general, clinicians are most interested in the force generated at the point of a heel strike and a toe off. The resultant GRF is comprised of the vertical, anterior/posterior and medial/lateral components. Often hemiparetic post-stroke patients tend to favour their unaffected side as a compensation tactic however, this can affect the progress of rehabilitation (Muro-de-la-Herran et al. 2014). GRF information can be used by the clinician to determine individual force distributions as a percentage of body weight, which helps to identify asymmetric loads. A typical ground reaction force plate is represented in Figure 2.2.

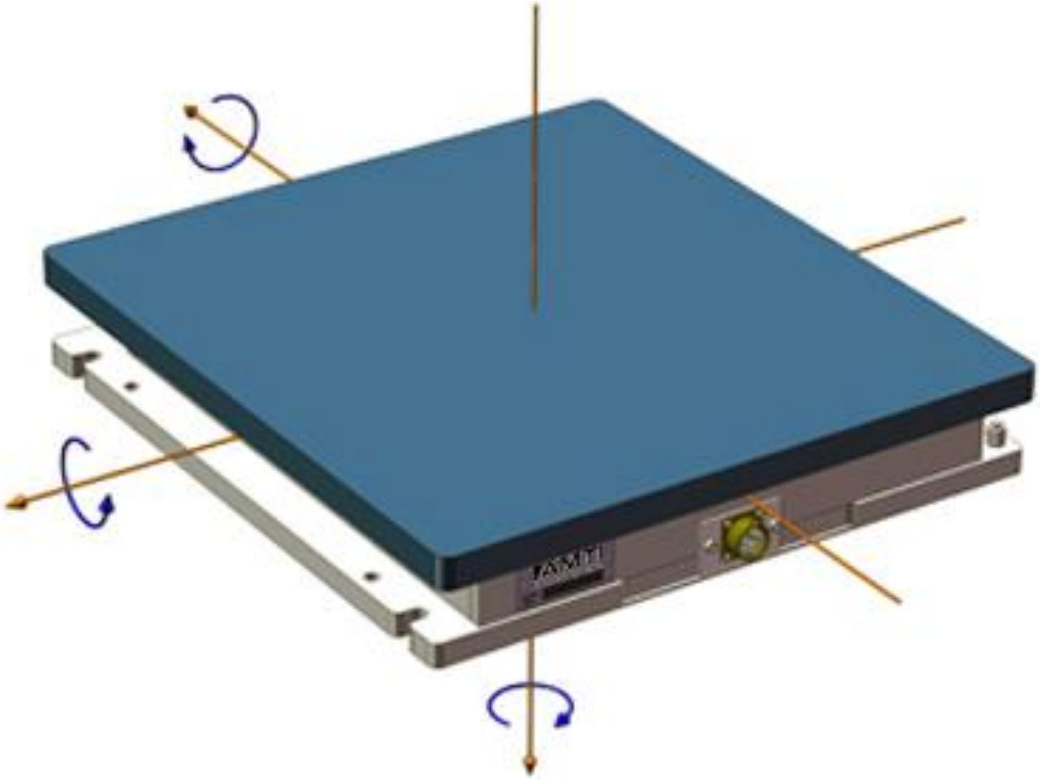


Figure 2.2: Diagram of AMTI force plate labelling the measurable forces and moments in addition to the ground force reaction. (AMTI 2016)

Plantar Pressure Mats

Plantar pressure mats are a made up of a collection of pressure sensing elements and come in either individual tiles or entire walkways, Figure 2.3. An advantage of pressure mats is that they are portable and much lighter that GRF plates. However, they can only measure the magnitude of the vertical component of applied pressure and often requires a patient to familiarise themselves to the limited contact area to ensure a natural gait cycle (Abdul Razak et al. 2012). Although pressure mats are more basic compared to GRF plates, their cheaper cost and greater level of portability make them a popular choice among clinicians.

Figure 2.3: Examples of platform-based foot plantar pressure sensor plate. (Abdul Razak et al. 2012)

2.3.2.2 Wearable Gait Analysis Systems

Many sensors can be attached directly to different parts of the body for quantitative analysis of gait. These systems include, but are not limited to, the shoe floor sensor, accelerometer, gyroscope, electromyography (EMG) sensor and goniometer.

In-shoe Sensors

The previously described floor sensors can be altered and installed to attach or fit into shoes to produce a portable force or pressure sensor. The in-shoe systems have been used in research as early as 1990 by Wertsch (Bamberg et al. 2008). who developed a system to measure pressure distribution of the foot. The major advantage of these systems is the portability allows clinicians to analyse patient conditions over extended periods of time, which is particularly beneficial to patients with chronic walking problems. Commercial systems include the Pedar, Tekscan and Moticon, etc. as shown in Figure 2.4.

Figure 2.4: Moticon OpenGo insole measurement device. (Moticon 2016)

Inertial Sensors

One method of full body motion detection is through the use of inertial sensors such as accelerometers and gyroscopes. Accelerometers measure acceleration forces along its principal axis by detecting changes in displacement with respect to the mass, according to Newton's 2^{nd} Law of Motion (Muro-de-la-Herran et al. 2014). In order for three-dimensional positioning in space an accelerometer with three axes is required. Through integration, parameters including velocity, position, angular velocity and angle of flexion with respect to the axis can be obtained. Gyroscopes detect rotation with respect to the reference frame measuring angular velocity. The size and weight of these sensors make them ideal for wearable devices and provides a cost effective alternative for full body motion detection compared to camera based systems. Figure 2.5 shows a study that examined the risk of falls in the elderly by using a miniature gyroscope to measure transitions between standing and sitting (Kobayashi et al. 1997; Najafi et al. 2002). Using previous data on the risk of falls in the elderly and the gyroscopic measurements taken during the experiment, it was shown that falls were able to be predicted. These sensor technologies can now be commonly found in modern smartphone devices. A separate study in 2006 proposed a simple gait analysing device based on a single three-axis accelerometer on a smartphone (Iso & Yamazaki 2006). The system was able to successfully identify and categorise gait patterns including walking, running, travelling up/down stairs and slow/fast walking speed transitions with an 80% accuracy.

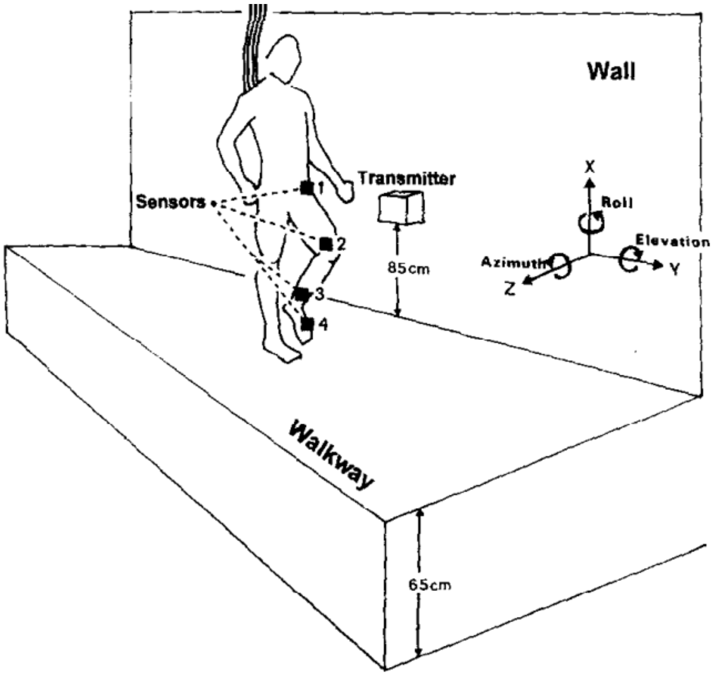


Figure 2.5: Example of an inertial system used for gait analysis. (Kobayashi et al. 1997)

Electromyography (EMG)

During a gait cycle the activity of the muscles can provide clinicians with information regarding the timing and strength of a muscle contraction. This muscle activity is typically measured indirectly using surface EMG electrodes (represented in Figure 2.6) that are placed over the skin, however, more invasive wire needle electrode EMG systems are available. EMG analysis is vital in assessing a patients' walking performance as it can help identify paresis, spasticity or even loss of muscle function. It can also be used in conjunction with gait kinematic analysis to compare the joint movements with the evoked muscular activity. (Wentink et al. 2016) applied EMG to predict the onset of gait initiation in patients with a leg prosthesis. The results showed that by recording the electrical activity at the prosthetic leg, the initial movement could be predicted up to 248ms prior to the inertial sensor data when the intact leg was leading.

Figure 2.6: Delysis wireless Trigno EMG sensor system. (Delsys 2016)

Goniometers

These flexible sensors calculate the magnitude of flexion by measuring the resistance changes of the sensor, in a similar manner to a strain gauge shown in Figure 2.7. They are fixed to a joint such as ankle, knee, hip, etc. and as the joint is flexed the sensor flexes proportionally, producing the measure of the kinematic angle. Goniometers were one of the first tools used to measure joint angles from a video as a post processing aid. A study by (Stuberg et al. 1988) and (Embrey et al. 1990) investigated the interrater reliability between clinicians who measured joint angles directly from a screen using a goniometer. The results of the two studies showed a very high interrater reliability but the research involved only two clinicians and a single subject. More recently (Dominguez et al. 2013), developed a digital goniometer for measuring the knee-joint position in orthosis.

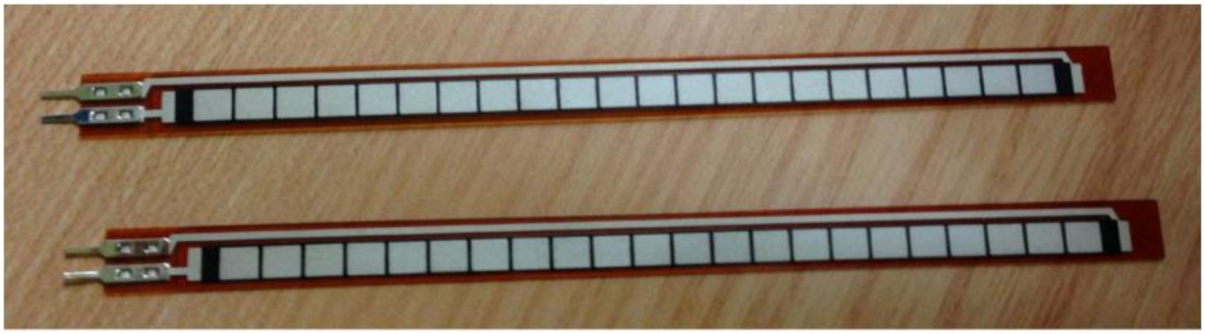


Figure 2.7: Flexible goniometers. (Muro-de-la-Herran et al. 2014)

2.3.2.3 Marker-Based Gait Analysis Systems

The use of optical sensors can be another method for motion tracking and with the vast improvements in camera technology, they can provide a gait analysis system with high accuracy and precision. The cameras are used to track visual markers attached to the body, which provide an estimation of position in time. In 1973, a Swedish psychophysicist Gunnar Johansson conducted studies on biological motion by placing reflective markers on specific joints of human subjects (Johansson 1973). The subjects were then flooded with bright lights which created high brightness contrast ratios between the markers and skin, resulting in the markers appearing as spots against a dark screen. The spots could then be tracked and related to the trajectory of human motion. This study was a breakthrough in human motion tracking and analysis and as a result, marker-based systems are classified as the benchmark for gait analysis systems. Current motion tracking systems can use either passive or active markers.

Passive Marker System

Passive marker systems use multiple cameras, typically between 1 and 16, that emit infrared light toward a predefined trajectory in the general direction of the object being tracked (Zhou & Hu 2008). The reflective markers are placed on specific joint location of body and are tracked in real time by the cameras which receive the reflected infrared light signal. The data is the captured and stored on a computer for post processing; this process is represented in Figure 2.8. The three-dimensional positions of the markers are reconstructed through the combination of multiple two-dimensional image data from the cameras. Commercially available systems such as the VICON motion capture system have advanced post processing tools which can calculate virtual joint centres and segment orientations though optimisation techniques. Once the software has created a model of the motion using the data from the markers, it can provide clinicians with the most accurate measurements of spatiotemporal gait parameters.

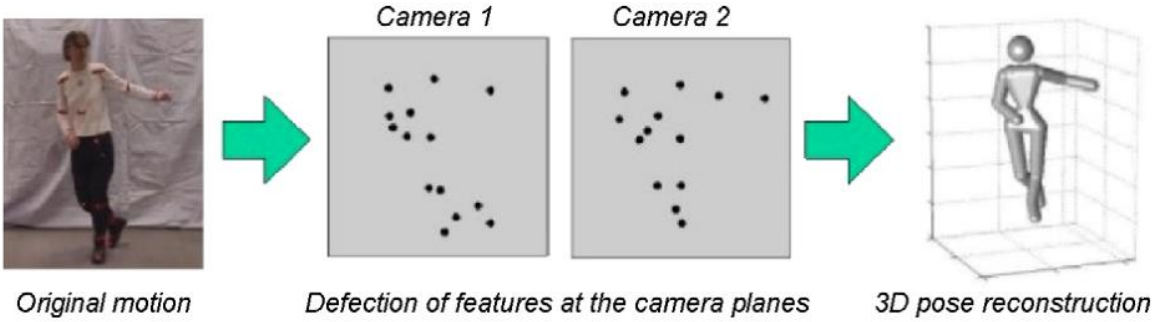


Figure 2.8: Three-dimensional human motion tracking using a passive maker system. (Ringer & Lasenby 2002)

Active Marker System

Unlike passive systems which use markers that only reflect the light back to the cameras, active systems are capable of emitting light directly which can increase the overall distance and volume of the capture space. While this technology was initially developed as a biomechanics research tool, modern applications of these systems include computer animation for movies and videogames (Zhou & Hu 2008). Marker-based motion tracking systems however, are not without their drawbacks and limitations. The markers can be unreliable, either moving or in some instances may completely detach from the body. Markers can also be obstructed by the body depending on the type of motion, often resulting in missed data capture, which are then estimated in post processing. Often gait analysis laboratories are installed with a combination of equipment, the use of cameras for motion tracking, force plates and EMG sensors can all be correlated for the most comprehensive analysis of human gait. As a result, these systems are very expensive and require large designated spaces for operation.

2.3.2.4 Marker-less Gait Analysis Systems

While marker-based systems are thought to be the gold standard in the clinical assessment of gait, the limitations behind that technology have garnered the interest of applying marker-less systems. Some of the video image processing techniques discussed have initially been developed for general human motion tracking, such as surveillance rather than for rehabilitation purposes (Nixon et al. 2006).

Time-of-Flight (ToF)

ToF cameras are used to capture complete three-dimensional scenes by measuring the time taken for an infrared light (IR) to travel from an emitter to an object and back to the sensor array, the principle of ToF is represented in Figure 2.9 The cameras are able to map the depth of a scene proportional to the time taken for the IR light to be received from an object and the known speed of light through air. The resolution of ToF cameras are restricted by the number of individual sensors in the array and as a result is typically low compared to standard video cameras (Muro-de-la-Herran et al. 2014). A different study was then conducted on gait analysis using a ToF camera, creating a marker-less system which can calculate gait parameters including speed, cadence, step length, stride length and range of motion (Jensen et al. 2009). The system was able to produce the gait parameters with very little error with depth used for the tracking, eliminating any clothing or background limitations and distractions. Although this proved to be an effective system, there are simpler more cost effective alternatives that can provide the same information.

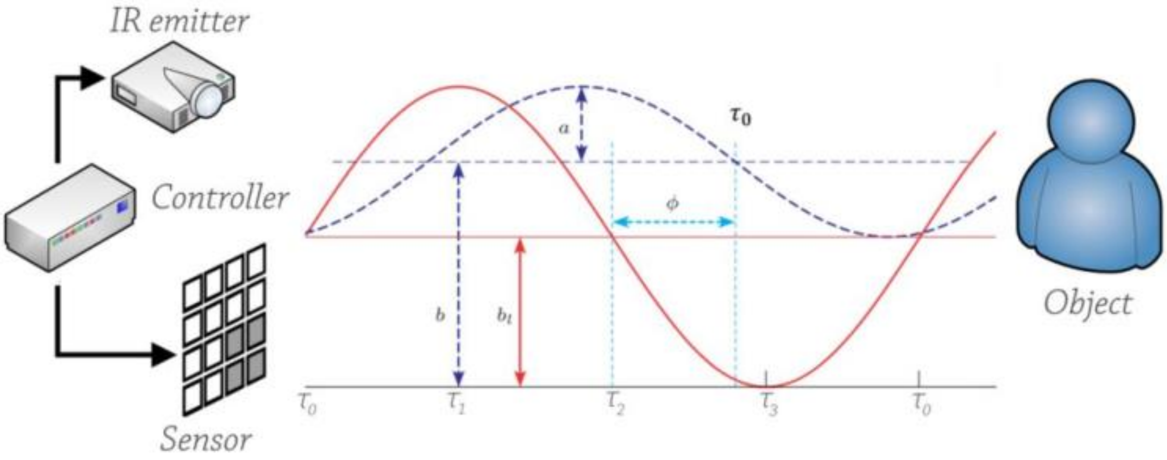


Figure 2.9: Principle of time-of-flight. (Muro-de-la-Herran et al. 2014)

Structured Light

Structured light is another common method for three-dimensional data acquisition. This system is able to map the depth of a scene by projecting a coded striped pattern which is then captured by a camera to produce the image, thus, each point in space can be defined by a stripe and pixel coordinate. At the point of intersection between the stripe and pixel a unique value, representing location of the point in space is obtained with respect to the original projection (Muro-de-la-Herran et al. 2014). In recent years, since the release of the Microsoft Kinect, structured light cameras have been a more common affordable alternative for three-dimensional motion capture. (Hu et al. 2011) used a Kinect sensor to develop a moving three-dimensional lower limb tracking system for mobility walkers. This system was designed to be a low cost alternative to marker-based systems such as VICON. Its portability and minimal setup ensured that the system could be used in more natural environments however, in its current state the errors of the system are much greater than other clinical equipment.

Video Image Processing

Modern technological advancements, in particular computational capabilities, have opened up new avenues for gait analysis using digital image processing. High resolution cameras combined with digital processing allows for high accuracy, marker-less systems at relatively low costs. A common digital processing approach to motion tracking is by focusing on human movement in a two-dimensional image plane. By simplifying the data, faster spatial calculations for the tracking system can be made. Using this two-dimensional system, the human body can then be modelled and tracked by either using explicit shape modelling or by silhouette shape modelling (Zhou & Hu 2008). Explicit shape modelling uses predefined cylindrical shapes to create a segmented body model and uses general knowledge of human movement to process the data. Alternatively background subtraction, whereby software is used to detect moving regions in an image to isolate each individual pixel relative to a static background, can be used to create a silhouette model. (Wang et al. 2005) developed a gait recognition system using a silhouette based analysis system that showed positive results. The major disadvantage behind background subtraction systems is that it is sensitive to dynamic scenery and lighting.

Two-dimensional systems will always have limitations due to depth and view angles. To create the most accurate representation of human motion, three-dimensional modelling technology can be employed. Typical three-dimensional analysis includes volumetric modelling and stick figure representation and has been a major interest for researchers, with a study in 1998 proposing a volumetric modelling system that utilises a series of spheres that has produced positive results (Chung & Ohnishi 1998). While the potential of marker-less motion capture technology is emerging, its current gait analysis applications are limited with respect to the accuracy and validity of quantifiable data compared to alternative gait assessment techniques.

2.4 Portable Video Gait Laboratory

The Portable Video Gait Laboratory (PVGL) is a collaborative project Dr Adrian Winsor and Flinders University. The aim of the project is to develop a device that is able to autonomously track a subject walking in a predefined straight line path while performing VOGA. The clinicians' ability to combine video with OGA has typically involved static cameras on tripods resulting in limited walking distances, or requires complex three dimensional VOGA technology. Thus, the PVGL project was conceived, aiming to provide a simple yet effective method for VOGA to clinicians analysing gait. The primary features were evaluated based on the current advantages and disadvantages of all the different VOGA methods. As such, the ideal PVGL will have recording capabilities of multiple gate cycles in both the coronal and sagittal planes and will be non-obtrusive to the patient allowing for natural, unaltered walking patterns.

2.4.1 Current Status

The PVGL project began in 2000, when the first prototype was developed by a Work Integrated Learning (WIL) student based at the Daw Park Repatriation General Hospital (Olivia Pallotta 2000). This system was limited to the technology and resources of that era and as a result sported low resolution black and white cameras fixed at waist height, to a bulky U-shaped body made from heavy steel and wood. The following year, a modified second prototype began development by Symonds (2001) and was completed by Conway (2002). This prototype featured a new fixed L-shaped frame and a remote control function to start/stop the motor. However, the system still operated using black and white cameras with limited viewing angles and was constructed from heavy, bulky materials reducing the portability of the device.

The project was then put on a 13-year hiatus before it was resurrected as the GaitScanner by Benjamin Schultz in 2015, represented in Figure 2.10. The previous iterations had since been destroyed, consequently the third working prototype was rebuilt from entirely new materials and updated technology. It was the most advanced version to date, taking full advantage of the modern tools currently available. The L-shaped frame was built from lightweight aluminium channelling and featured an updated collapsible design for improved compactability and portability. Aluminium tubing was used for the upright camera mounting poles, which were secured by a slightly weak hinge mechanism. Unlike the previous prototypes, the cameras did not have a fixed mounting location. As such, the height of both cameras could freely be adjusted for an individual subject. The cameras used were capable of capturing digital colour footage at high resolution. In addition to the upgraded resolution, the new system featured an increased field of view able to capture the entire body within the frame. While the body frame was a vast improvement over the previous prototypes, the lack of an encasing was a weakness to the overall design.

Figure 2.10: GaitScanner CAD assembly structural design. (Schultz 2015)

The PID control system control system used dual infrared sensors to automate the devices' movement. The main sensor was programmed to maintain a fixed 145 cm distance away from the subject. The system was adequate at maintaining the distance, however, it was unable to accommodate for rapid acceleration and deceleration. A second control algorithm was implemented to address these issues, whereby the clinician could set a fixed speed and direction of the device. The second sensor was installed as a safety mechanism to detect any obstructions in front of the device during operation. While the control system is able to function on a basic capacity, alterations need to be made in order to make this device capable in a clinical environment.

2.4.2 Similar Devices

The GaitScanner is not the only PVGL device currently in development. Like the PVGL, these other devices are all designed with the same goal of autonomously monitoring the patient's gait using a robotic device. Although the fundamental premise is similar the means by which these devices achieve this goal differ significantly.

A popular approach for portable gait analysis devices is to use a Microsoft Kinect sensor to provide colour and depth image maps. (Bonnet et al. 2015) proposed an affordable mobile platform for pathological gait analysis, focusing primarily on the freezing of gait, which is the temporary, involuntary inability to move when initiating gait. Driven by a Kinect sensor, shown in Figure 2.11, the device is able to follow a patient at a constant distance while also being able to estimate the gait spatiotemporal parameters. The performance of the tracking system, stride length accuracy and joint angle estimation were tested and evaluated against an eight camera VICON system. The results showed that the accuracy of the stride length was within 2.5 cm, which is sufficient for several clinical applications, but due to the low sampling frequency of the Kinect sensor the temporal variability in gait events cannot be studied. Detection of freezing of gait was achieved by monitoring the forward progression of the robot. However, not all instances of stationary motion of the robot can be attributed to freezing of gait in a patient and as such the recorded video footage at that point in time must be reviewed.

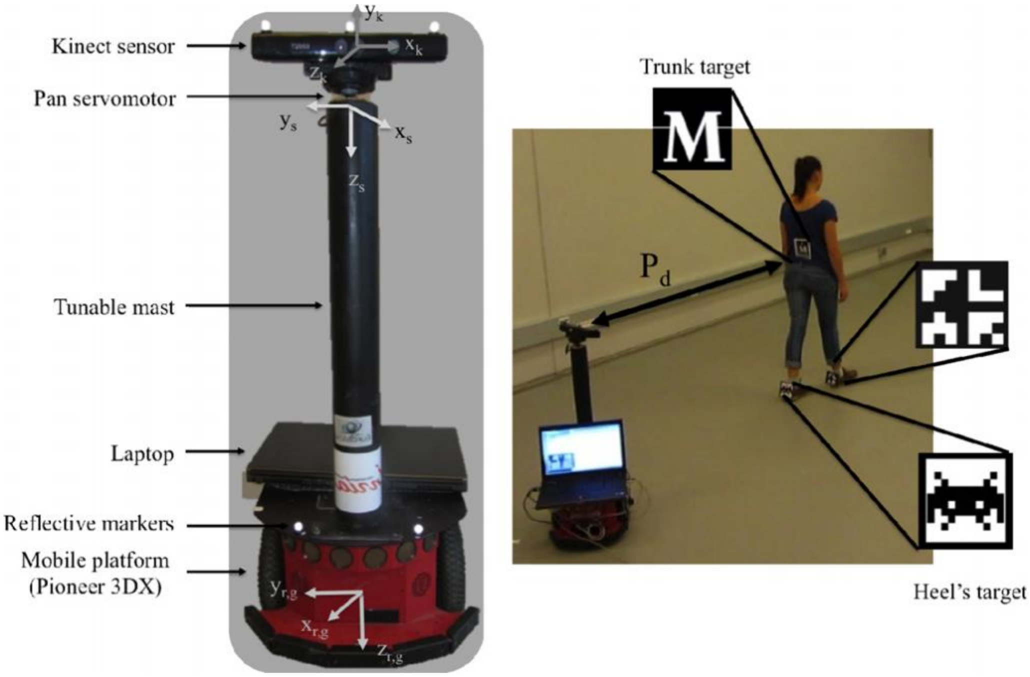


Figure 2.11: Detail of the proposed system and experimental setup by (Bonnet et al. 2015).

A similar device using the second generation Microsoft Kinect was proposed by (Ťupa et al. 2015), see Figure 2.12. In addition to the infra-red and depth sensing capabilities, the new Kinect is able to simultaneously track up to six people and can provide position information of 25 joints from two people. This system tracks the patient by positioning the robot in front utilising backwards viewing cameras, claiming to provide a more natural and unobstructed recording environment. The primary gait information obtained from this system are the patient walking speed and stride length. A three-dimensional model can be created if the appropriate post processing techniques are applied. The reliability of the tracking and the validity of the data cannot be commented on as the system has only just entered the testing phase.

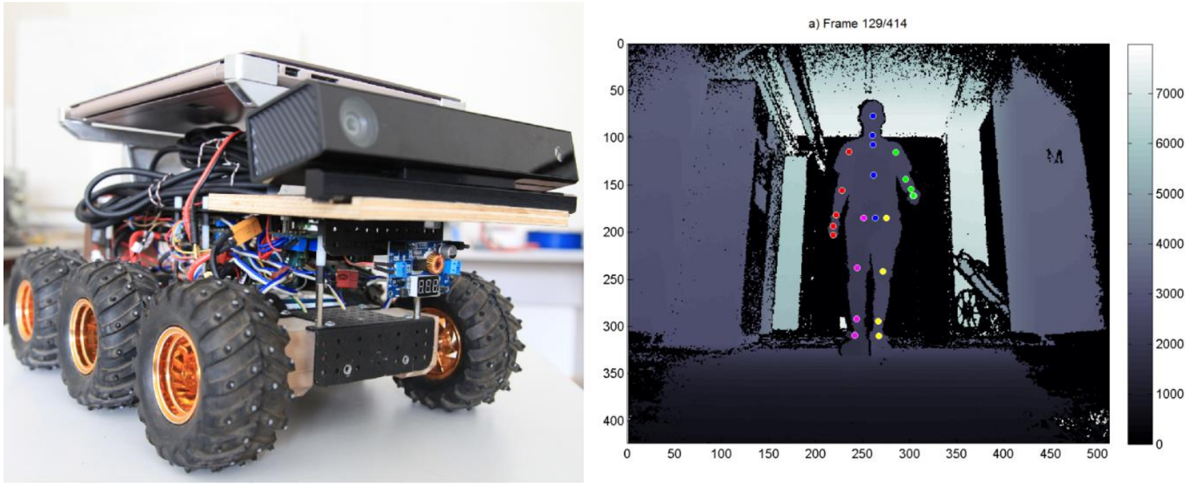


Figure 2.12: Proposed mobile robotic platform with Kinect and depth map with highlighted body joints. (Ťupa et al. 2015)

Both of the discussed portable gait analysis systems utilised a single Kinect camera based system in the coronal plane. They aim to produce basic temporal and spatial gait characteristics while calculating the more complex kinematic data using three-dimensional computer modelling. In the conceptualisation phase for the previous iteration of PVGL the Microsoft Kinect was also identified as a possible sensing system. However, due to primary differences in the desired outcomes the low resolution, slow frame rate, required power and sheer size of the Kinect, the device was ultimately disregarded (Schultz 2015).

The area of autonomous robotic gait analysis systems is a relatively new concept with few devices in development and nothing currently commercially available. While the early stage PVGL prototypes and the proposed systems (Bonnet et al. 2015; Ťupa et al. 2015) may not be completely ready to use in a clinical environment, they present valid methods of analysing gait in a novel and innovative manner and have the potential to be adapted into a device for use in both a clinical and home environment.

2.5 Control Systems

Over the past decade the number of tracking control robots have increased greatly. For these autonomous robotic devices to function, a control system capable of processing large amounts of complex information in real time must be developed. Before designing a control system for the PVGL the different options must be reviewed in order to identify the best method of implementation. The two most common systems used in tracking robots are PID and fuzzy logic controllers. These control systems are discussed in the following subsection.

2.5.1 PID Control

A classical approach to a model-based control system is PID. A PID controller is dependent on three different factors, namely the proportional gain K_p, integral gain K_i and the differential gain K_d. The three parameters combine to minimise the error with respect to a predefined value or set-point (Mehrotra et al. 2011).

- K_p – the proportional control component determines the total amount of control signal output by weighting the input error, as such higher values result in a faster controller response to monitor the error.
- K_i – the integral control component is associated with reducing the steady state error resulting from the proportional gain. It is able to do so by accelerating the output to the desired value. As the input is consistently changing depending on K_p, the integral component must be calculated in real time, adding to the overall complexity of the control system.
- K_d – the differential control component helps by decreasing the overshoot created by the other parameters and effectively operates to stabilise the control system. Similar to the integral control component the differential control component must be calculated in real time.

Most robot controllers operate by sensing a particular feature. The current PVGL utilises a PID control system with a predefined distance as the set-point. An infra-red sensor positioned by the coronal camera of the system is used to detect the distance from the patient and serves as the input to the control system. The system will work to reduce the error such that the input is closer to the set-point value, which is achieved through accelerating or decelerating the system.

A study by (Kawamura et al. 1988) was able to show the validity of using a PID control system in a tracking robot with guaranteed accurate results provided that a large velocity feedback gain is set. A separate study by (Normey-Rico et al. 2001) presented a simple mobile path tracking robot using a PID controller. While the application for these robots differ, the underlying principles behind the control system can be taken into consideration when developing a control system for the PVGL.

2.5.2 Fuzzy Logic

A newer alternative to the linear PID controller is fuzzy control, which is based on a system that represents natural human thinking compared to traditional methods. In general, tracking robots must process a range of information including sensor data and obstacle avoidance before determining the output position. As a result, it can be quite difficult to create a controller using conventional systems as the constraints are constantly varying at all points in time. (Li et al. 2004) developed a fuzzy target tracking control system for an autonomous mobile robot using infrared sensors. The robot is able to navigate using a kinematic model which helps define every action for the given sensory information.

Although fuzzy control systems have the ability to process nonlinear models with higher accuracy and reliability compared to classical methods, it is still a relatively unfamiliar process and was reported that in Japan over 90% of control loops are still based on PID systems (Misir & Malki 1996). However, fuzzy control theory is developing to become a powerful tool that call allow systems to adapt and learn, to closely replicate a human mindset.

2.6 Patent Search

The PVGL was conceived to provide a cheaper, portable and more accessible device for both clinicians and patients. As such, currently there are no known commercially available devices with this functionality. A patent search for this project was last completed on 26 October 2015, in order to ensure there have been no new patents that may challenge or affect PVGL a revised patent search was conducted. The criteria for the search was based around an autonomous human motion tracking device with the purpose of recording a persons' gait. To conduct a search that would yield the most possible results the following Boolean statement was used in the World Intellectual Property Organization (WIPO) database:

ABSTRACT: ((robot OR autonom* OR track OR follow) AND (human OR person OR people OR patient) AND (gait OR motion OR walk*) AND (record OR video OR analys*))

2.6.1 Patent Search Summary

After conducting the patent search, as of 25 July 2016, a total of 154 patents from different countries were relevant to the key words used to search the WIPO patent database. The entire list was then scrutinized and scaled based on similarity and relevance to the PVGL. The majority of the patents were proposing new computer algorithms and systems for the post processing of video data to extract relevant spatiotemporal gait parameters. The following patents were deemed to have the highest similarity to the function of PVGL however none to the extent that will have a negative impact of the patentability of the proposed device.

Motion analysis system employing various operating modes

ID number: US4813436A, Figure 2.13
Publication date: 21 March 1989
Inventor(s): Jan C. Au

The system described utilises two cameras (positioned at coronal and sagittal orientations toward the subject), body markers and pressure sensitive shoes. This system also required the use of a strobe to reflect light onto the body markers, which would then be visible to the cameras. The data is stored and processed to provide digital information regarding the subjects' gait characteristics, which then can be used by a clinician to make an assessment compared to a normal user. This patent expired in 1993 but has since been referenced by over 100 different patent and still remains one of the original patent proposals for a complete VOGA system.

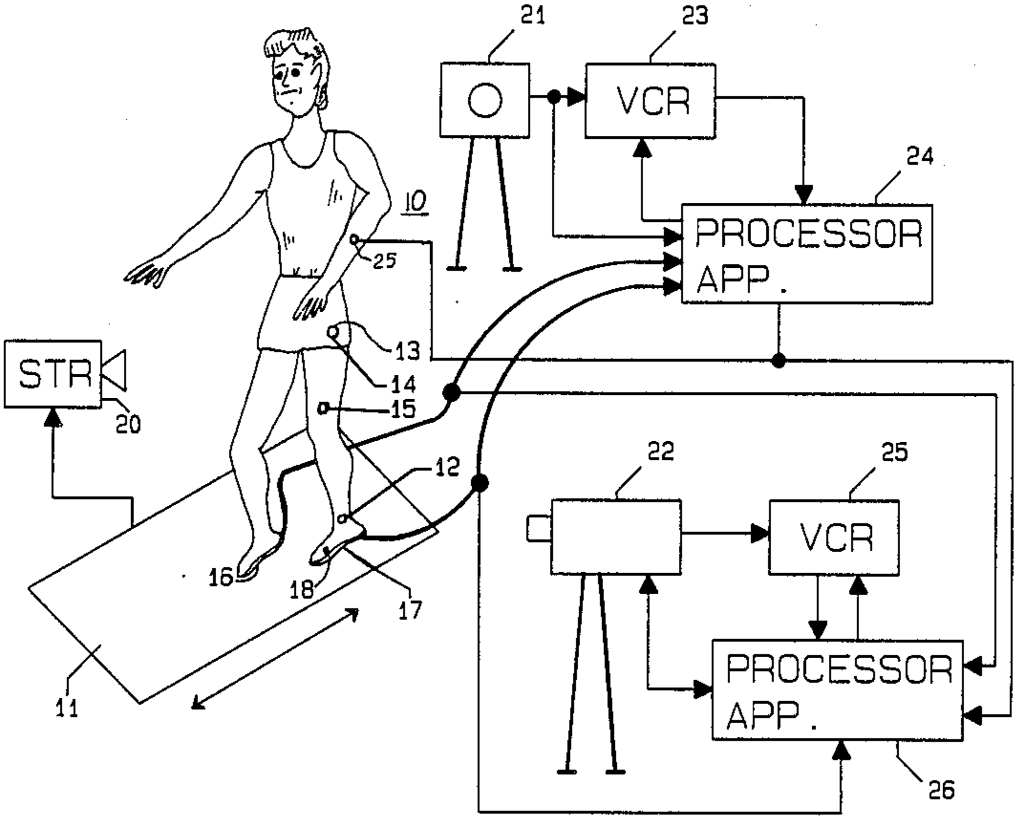


Figure 2.13: Patent US4813436A. (Au 1989)

Portable ranging system for analysing gait

ID number: US5831937A, Figure 2.14
Publication date: 03 November 1998
Inventor(s): Richard F. ff. Weir, Dudley S. Childress, Joseph N. Licameli

This system is a portable gait analysing system that uses infrared and ultrasound technology to produce data, which is then processed at a computer terminal. A wireless unit attached to a subject receives infrared signals from the base unit and vice versa for ultrasound signals This ranging system is one of the earliest proposals of a wireless system with the primary purpose of analysing gait. However, the measurement error increases significantly when the distance from the base unit is greater than 10 m, restricting the overall measurement distance.

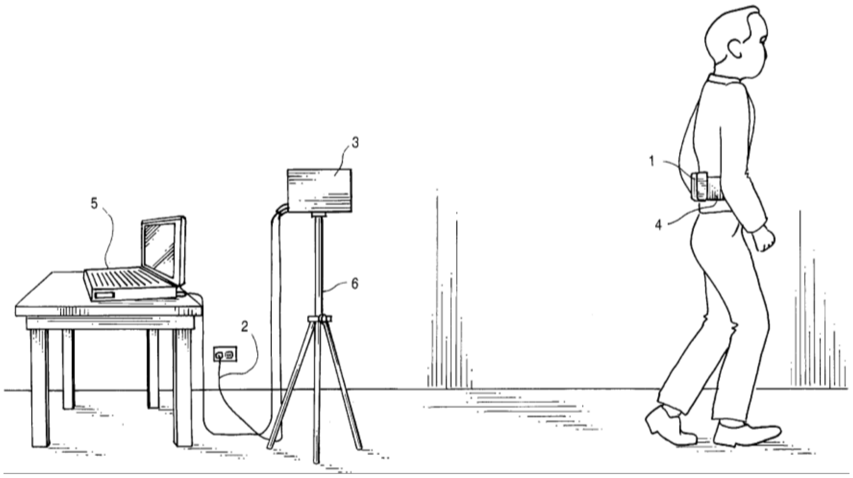


Figure 2.14: Patent US5831937A. (Weir et al. 1998)

Portable system for analysing human gait

ID number: US6836744B1, Figure 2.15

Publication date: 28 December 2004

Inventor(s): Fareid A. Asphahani, Hwa C. Lee

This patent describes a completely portable gait analysis system in form of a wearable shoe type device. The device has accelerometers, rate sensors, force and pressure sensors which all combine at the processing unit The gait parameters are then displayed on a LCD. This system does not use real-time video footage to assist with the analysis of gait and as such it operates based on entirely different principles compared to PVGL.

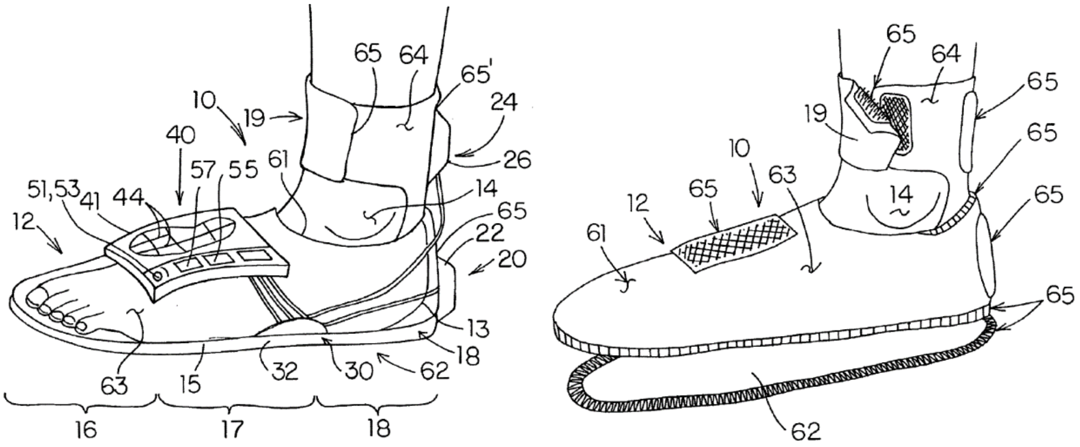


Figure 2.15: Patent US6836744B1. (Asphahani & Lee 2004)

Device for analysing gait

ID number: US20090198155A1, Figure 2.16
Publication date: 06 August 2009
Inventor(s): Stephane Bonnet

This system describes a device for analysing the gait of a person using a wearable magnetometer which generates a signal that represents the projection of the tibial segment onto a sagittal plane of the magnetic field. The signal processor has the capability to identify key phases that are indicative of the patient's gait. Similarly, like the aforementioned wearable devices, this system analyses gait through means of digital signal and data representation rather than through direct video footage like the PVGL.

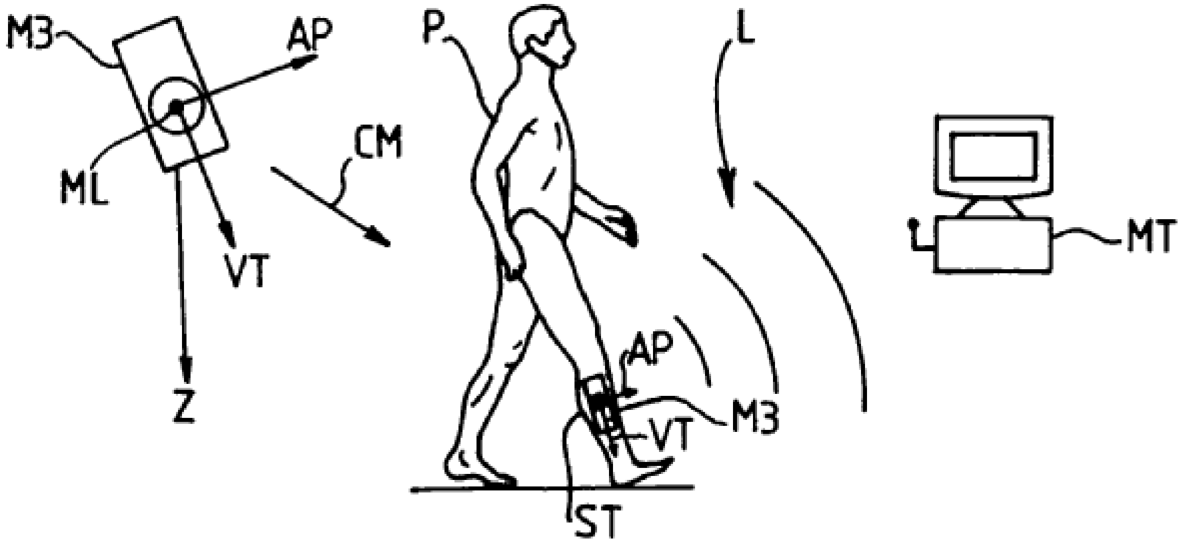


Figure 2.16: Patent US20090198155A1. (Bonnet 2009)

Human-tracking method and robot apparatus for performing the same

ID number: US20140107842A1, Figure 2.17
Publication date: 17 April 2014
Inventor(s): Young Woo Yoon, Do Hyung Kim, Woo Han Yun, Ho Sub Yoon, Jae Yeon Lee, Jae Hong Kim, Jong Hyun Park

The patent describes a robot device designed for human tracking, by analysing the current image frame and comparing it to the previous image to determine location of a user. The device can identify varying depths which is used to aid redirection when obstacles or objects obstruct the path of the robot. While the human tracking and video is relevant, it is not a device designed for gait analysis and as a result will not affect the patentability of the PVGL.

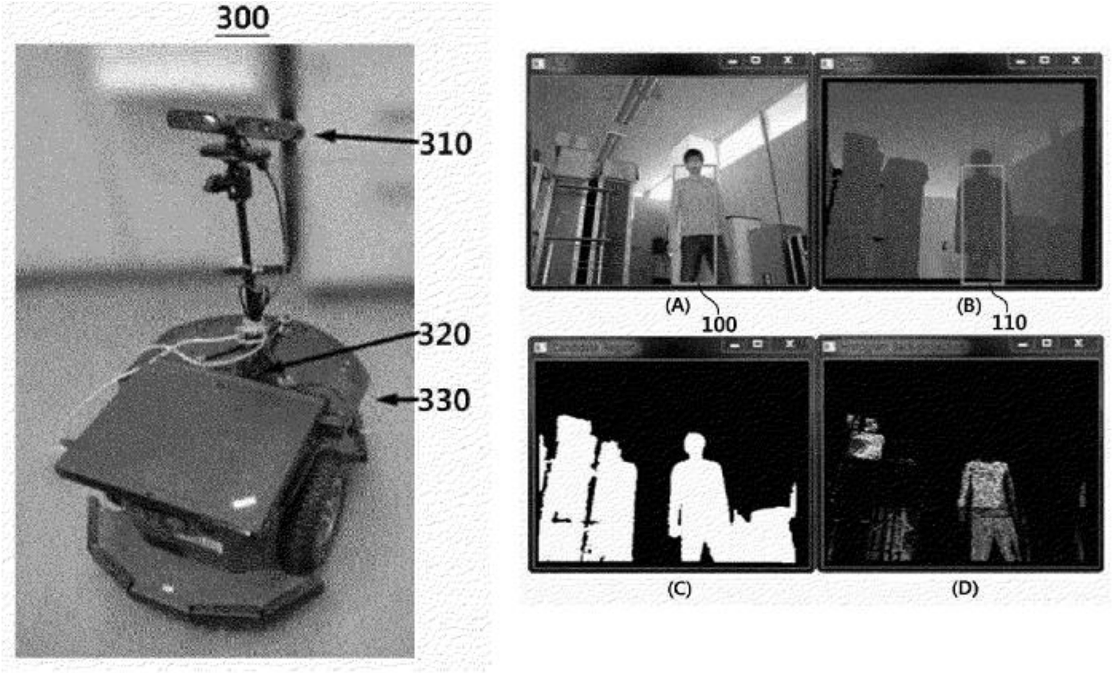


Figure 2.17: Patent US20140107842A1. (Yoon et al. 2014)

2.7 Future of Gait Analysis

Gait analysis is a forever evolving field of medicine with modern technological advances allowing for most accurate assessment, diagnosis and treatment to date. Video gait analysis techniques can produce three-dimensional gait models with millimetre precision, different sensor technologies can show data on muscular activity and the forces applied by a limb can be quantified. In its current state however, these advanced techniques are not being adopted by all clinicians. While the equipment may be designed to produce a range of gait parameters allowing clinicians to make the best decisions for their patient, often it is not viable or acceptable to use these precise measurement procedures on patients.

To obtain quantitative data all of the aforementioned systems require regular calibration and sampling to function without error. They require highly skilled professionals for operation and occupy large dedicated workspaces, as such these complicated systems cannot be used outside of a clinical environment. Wearable gait analysis systems attempt to address the portability and space issues, however, studies suggest that they can have negative effects toward a patients’ gait. It is important that clinicians consider the physical condition of the patient before compelling patients to undergo assessment using this technology. By placing patients in closed environment or when affixing sensors to the body, it can cause patients to subconsciously alter their gait patterns different to their natural motion and ultimately produce inadequate results.

Even with all these tools at their disposal, clinicians still favour more primitive forms of technology, in particular OGA. The literature suggests that clinicians prefer a system that is easy to operate with, minimal equipment, short setup times and allows the patient to walk in the most natural everyday environment with minimal distractions. OGA provides a moderate to good representation of a patient’s gait in real time and this visual feedback can be used to help correct the patients’ movements immediately without stopping the gait cycle. Compared to qualitative VOGA, which requires post processing in order to provide feedback. After reviewing the relevant literature, it is evident that the field of gait analysis will continue to strive toward an ultimate assessment system that addresses the need for a user friendly, portable, real time system at an affordable price while not sparing accuracy and precision of data.

3.

Project Definition: Requirements and Specifications

Before any conceptual designs for a prototype can come to fruition, the client's vision for the project must be clearly defined. The project definition was formed through a combination of establishing a clear set of requirements with the recommendation of the client. The list of requirements was then further developed to form the basis for the primary project specifications and to finalise the project definition.

3.1 Requirements

After meeting with the client to discuss the projects primary needs and necessities, a complete list of requirements was created, considering the enclosure, control system and the video playback program. The requirements along with their level of importance to the project is detailed in Table 3.1. The requirements can be further categorised into existing and new requirements, which are discussed throughout this section.

Table 3.1: A summary of the project requirements accompanied with the level of importance

No. #	Requirement	Level of Importance
1	Must capture subject gait from both the coronal and sagittal planes	B
2	Must not impede patient gait	D
3	Must be durable	G
4	Must be easy to operate	H
5	Must be of low cost	K
6	Must accommodate all users	F
7	Must be portable	E
8	Must have multi-surface capability	L
9	Must easily integrate with wearable 3rd party systems	M
10	Must reduce input lag upon acceleration/deceleration	A
11	Must have an enclosure for electronic components	C
12	Must record basic spatiotemporal data	I
13	Must have a simple means of video playback	J

3.1.1 Existing Requirements

The following requirements have been addressed in previous iterations of the PVGL project, however they have also been identified to have a high importance and must again be considered for the current project.

3.1.1.1 Requirement #1

Must capture subject gait from both the coronal and sagittal planes

Importance rating: B

For all of the previous PVGL prototypes the client's primary desire was to capture uniform two-dimensional video footage of a patient's lower body in the coronal and sagittal planes and is no different for this iteration. In order to satisfy this requirement, a minimum of two cameras are needed, they must each be positioned such that they can capture the subject at approximately equal distances to ensure uniform video footage. The cameras should be height adjustable to ensure the lower body can always be centralised in the video frame regardless of a subject's height.

As this was a key requirement for the previous prototype an in-depth review of commercially available cameras was previously made. Considering picture quality, cost, size and implementation plausibility, two GoPro video cameras were selected as the primary candidate. To reduce project cost these cameras can be reused, however options such as file accessibility, frame rate, file size and record/playback control must all be taken into consideration. As the cameras are currently operated individually a method of synchronising the cameras must be devised. Camera synchronisation is vital when analysing the subject gait data, as all key gait events must be time correlated for identification.

3.1.1.2 Requirement #2

Must not impede patient gait

Importance rating: D

As mentioned in the previous requirement, the PVGL must not impede subject gait. The primary function of the device to capture the gait motion of a subject, the capture must show the clinician video of a subject's gait that is indicative to their natural walking motion. If the device is to impede the subject in any way causing the subject to walk in an uncharacteristic manner, the captured video and any related data cannot be used for further analysis. As a result, this requirement is of very high importance and will also need to be considered when addressing requirement #3 and #9, ensuring all subjects using the device can do so in an unhindered manner.

3.1.1.3 Requirement #3

Must be durable

Importance rating: G

Expanding on requirement #3 not only does the device need an enclosure to protect the electronic componentry, but the device as a whole must be durable to withstand general use. The PVGL is intended to be used in a clinical environment, however, the key features allow the device to be used outdoors or taken to patient homes and or external facilities. This requirement along with requirement #11 will heavily dictate the overall structural design and what materials will be used when building the new prototype. When designing for durability the level of strength needed will be considered and analysed to ensure it is not under or over engineered.

3.1.1.4 Requirement #4

Must be easy to operate

Importance rating: H

The client has a specified that the device must be simple to operate by an individual user. In accordance with requirement #11, in order to be easy to operate the device must have certain structural conditions; including size, weight and complexity of interface. As the device is designed to be transported to various locations, it is important that the majority of the population can handle the device without difficulty. The complexity of the control interface and methods for data acquisition are important areas to consider as not all of the clinicians and other users will have technical experience. To ensure all users have an appropriate understanding of the device a basic user manual will be created.

3.1.1.5 Requirement #5

Must be of low cost

Importance rating: K

Current gait analysis systems are often found in large hospitals and rehabilitation centres, often this can be attributed to the high costs involved in acquiring such a system. The PVGL looks to address this issue by providing clinicians an affordable device capable of capturing footage for video gait analysis. The funds for the project is largely controlled by the client along with a small portion of allocated project money provided from Flinders University. It will be important that the project does not exceed these funds, thus, all materials purchased will be recorded in a detailed cost analysis.

3.1.1.6 Requirement #6

Must accommodate all users

Importance rating: F

Since all subjects will not have the same condition, the major challenge is to ensure the device is able to accommodate all users. As the one device will facilitate both male and female subjects, the variable height, width, age and gait ability must be considered. Requirement #1 previously addressed the importance of variable height adjustable cameras to ensure the lower body is centred on all subject captured footage. While subject width does not vary as greatly compared to height, many subjects require the assistance of walking aids, these aids can range from prosthetics, orthotics, through to a variety of walk assist frames. Thus, the device must ensure the position of the coronal camera does not interfere or impede subject gait.

3.1.1.7 Requirement #7

Must be portable

Importance rating: E

Current gait laboratories are primarily located in specialised hospitals and rehabilitation centres, although these facilities are often equipped with state of the art technology it is not always possible for people to travel to these prescribed locations. A major feature of the GaitScanner its portability, which aims to address this very issue. The device will provide comprehensive video gait analysis to a wider user base who may reside in residential care homes, hospitals, clinics and even to the people still living at home. Each prototype revision has focused on portability to help further cement the viability as an in-home monitoring device. Requirements #3 and #6 must also be considered when designing a portable device, it is crucial that the structure is lightweight, yet durable so none of the components will be damaged through transport to and from different locations.

3.1.1.8 Requirement #8

Must have multi-surface capability

Importance rating: L

Requirement #11 expresses the importance of portability, however in order for the device to fully satisfy this requirement the GaitScanner must be fully operational in various environments. While the device is primarily intended for use indoors, due to the portability it is not unusual to see the device used in outdoor environments. As such then completed device must undergo rigorous testing in various environments and surfaces.

In addition to the indoor and outdoor environments, it is important to consider the stability when moving over a flooring surface. Stability of the cameras are essential for a clinician to make an accurate analysis of a patient’s gait, however, not all flooring surfaces are level. Thus, the structural integrity of the device must allow for smooth traversal across all surfaces to ensure any errors or issues during video capture are minimised.

3.1.1.9 Requirement #9

Must easily integrate with wearable 3rd party systems

Importance rating: M

While the primary function of the GaitScanner is to capture video footage of the subject in both the coronal and sagittal planes to allow a clinician to monitor or diagnose a condition in a rapid manner using minimal equipment. The client has also identified the possibilities to combine and integrate with a wearable quantitative gait analysis system to record spatiotemporal data otherwise unobtainable with the GaitScanner alone. By having the option to measure kinematic properties it will establish the GaitScanner into an all-round gait analysis device.

For any wearable system to be used in conjunction with the GaitScanner it must not interfere with the fundamental operation of the device. As such the any design considerations to the GaitScanner will be made prior to the integration of any 3rd party systems. The plausibility of this can will then be investigated and recorded.

3.1.2 New Requirements

In addition to the revised requirements, a list of new requirements where identified to further enhance the project. These requirements where created such that the quality of the final device will be improved and as a result form the basis for this project.

3.1.2.1 Requirement #10

Must reduce input lag upon acceleration/deceleration

Importance rating: A

After a thorough review of the current prototype the client identified the control system of the device to be the greatest area of interest. In its current state the device is able to autonomously track human locomotion directly forwards and backwards, however, there exists an input time delay upon acceleration and deceleration. In an ideal system the device would remain at a constant distance from the subject at all times adjusting for any changes is speed. The time delay is responsible for both an overshoot and undershoot when the subject respectively increases or decreases their walking speed. As a result, when the sensor is processing patient distance the device is unable to uniformly adjust without causing an overshoot or undershoot before reaching the set-point distance. This issue also presents issues regarding both the coronal and sagittal camera and their ability to maintain a uniform capture. Since the input subject speeds are dependent on the severity of the patients' condition, the GaitScanner must be able to accommodate the varying speeds between different subjects.

3.1.2.2 Requirement #11

Must have an enclosure for electronic components

Importance rating: C

The client has expressed his desire to use the device for clinical trials, to satisfy this requirement the device must comply to basic safety regulations. The previous prototype was a successful proof of concept and the next step for the GaitScanner is to create a prototype that is suitable for a clinical environment. This means that all exposed wires and electronic componentry must be covered. When deciding on the ideal enclosure, a complete design evaluation must be made while also taking requirements #6 and #11 into consideration. Not only can exposure present an opportunity for to damage the components, but it also poses as a possible distraction to the subject. It is crucial that distractions are minimised as studies have shown that subjects can subconsciously alter their gait pattern if they feel discomfort or are in an unnatural environment (Coutts 1999).

3.1.2.3 Requirement #12

Must record basic spatiotemporal data

Importance rating: I

It was previously identified that the GaitScanner has the potential to record basic spatiotemporal data, in the form of subject speed and total distance travelled. This would provide information to the clinician in addition to the data obtained from the video footage. This data would help greatly during the monitoring and diagnosis of subject conditions. In order to extract this data, the control system must be programmed to store the information in a logical manner that can be accessed at a later date for further analysis.

3.1.2.4 Requirement #13

Must have a simple means of video playback

Importance rating: J

The current system does not have any means of simultaneous video playback. For a clinician to analyse the recorded video footage they are required to play the coronal and sagittal plane view videos individually. By incorporating simultaneous parallel playback of the video footage it will provide a simpler way to diagnose and monitor a subject’s condition. The program must have an interface that is easy to use by all clinicians without requiring any technological expertise.

3.2 Design Components

All of the defined requirements must be taken into consideration as collective when designing and developing the GaitScanner. However, to ensure the project is to be completed successfully within the time constraints, the requirements can be used to help categorise and streamline the project into focused subsections. Three primary components were identified; the structure, control system and video playback. By subdividing the project into these three sections it is easier to identify which requirements have a larger impact on certain aspects of the device.

Device Structure

The mechanical aspect of the project is solely related to the structure of the device. The structure is the housing for all components and will provide the means of fixing the cameras around the subject when the device is in motion. The structural choices will determine the level of portability and its durability when used on different surfaces. The structure must satisfy the requirements while ensuing that subject gait remains unimpeded.

Control System

The electronic component is responsible for the control system, which encompasses the sensor input through to the computational processing and finally the output. The client expressed his greatest interest toward the project as the improvement of the control system to address the delay issues. The complexity of operating the device will also be heavily dependent on the interface used to control the movement of the device.

Video Playback

While video playback is not directly related to the device, it is a pivotal aspect of the GaitScanner as a whole. If a simple GUI interface can be developed it will help the clinician to view the recorded footage and better monitor or analyse the subjects’ gait patterns. A GUI interface feature would help promote the device to clinicians as a complete gait analysis tool rather than just a standalone device.

Some requirements will directly impact both the structural properties and also the control system of the device. Table 3.2 details the relationship between the requirements and design components for the project.

Table 3.2: List of requirement with project design affiliation

Device Structure	Must capture subject gait from both the coronal and sagittal planes[1]
	Must not impede patient gait
	Must be durable
	Must be of low cost
	Must accommodate all users
	Must be portable
	Must have multi-surface capability
	Must have an enclosure for electronic components
Control System	Must be easy to operate[1]
	Must easily integrate with wearable 3rd party systems[2]
	Must reduce input lag upon acceleration/deceleration
	Must record basic spatiotemporal data
Video Playback	Must have a simple means of video playback

1 Requirement also must be considered for video playback

2 Requirement also must be considered for device structure

3.3 Specifications

The project requirements must be further developed into project specifications before the conceptualisation phase can begin. The specification phase involves taking the defined requirements and quantifying them such that they can be successfully carried out over the course of the project. Table 3.3, Table 3.4 and Table 3.5 address any ambiguities by providing a specification and target value along with the units and a direction of improvement for the three key project areas, device structure, control system and video playback respectively.

3.3.1 Project Specifications

Table 3.3: Device Structure Specifications

Specification	**Units**	**Value**	**Direction of Improvement**
Extended dimensions	mm	1200 x 1500 x 300	↓
Compact dimensions	mm	600 x 500 x 300	↓
Weight	kg	<10	↓
Cost	$	<$300	↓
Lifespan	years	>5	↑
No. exposed components	components	<5	↓
Time to setup	seconds	30	↓
Height adjustability	mm	>600	↑
No. of cameras	cameras	2	↑
Durability (drop height)	mm	>200	↑
Injuries	persons/year	<1/year	↓
User age	age (years)	>12+	↓
No. of surfaces	surfaces	>5	↑
No. of separate parts	parts	<3	↓
Water resistant			
Third party support	yes/no	yes	=

Table 3.4: Control System Specifications

Specification	**Units**	**Value**	**Direction of Improvement**
Acceleration	m/s^2	1.5	↑
Latency/delay	ms	<500	↓
User age	age (years)	>12+	↓
Distance from subject	mm	1500 x 1200	=
No. of controllers	controllers	<2	↓
Cost	$	<$300	↓
Accuracy	mm	<50	↓
Battery Life	hours	>20	↑
Time to emergency stop	seconds	<5	↓

Table 3.5: Video Playback Specifications

Specification	**Units**	**Value**	**Direction of Improvement**
User age	age (years)	>12+	↓
CPU usage	RAM	<2GB	↓
No. of displays	displays	2	↑
No. of buttons	buttons	<5	↓
Playback framerate	frames	>20	↓

3.3.2 Budget Constraints

In 2015 the client provided a $5000 budget toward the GaitScanner project, the majority of these funds were spent towards building the 3rd prototype. However, most of the previously purchased components can be reused and any additional hardware can be purchased with the remaining funds. Additionally, the University has supplied a total of $500 that can be used towards any project related purchases.

3.3.3 User Constraints

A key requirement was to ensure that the device is accessible to a wide range of users. The base age of 12 years old was selected however age is not the only limiting factor. Simplicity/ease of use across all three components of the project was identified. As such a minimum setup time of 60 seconds was selected to ensure preparation would not deter clinicians from using the device. The compact size and weight was set to be less than 600 x 500 x 300 and less than 10 kg such that it would be portable and would not inconvenience the clinician when transporting it to and from various facilities.

3.3.4 Human Gait Constraints

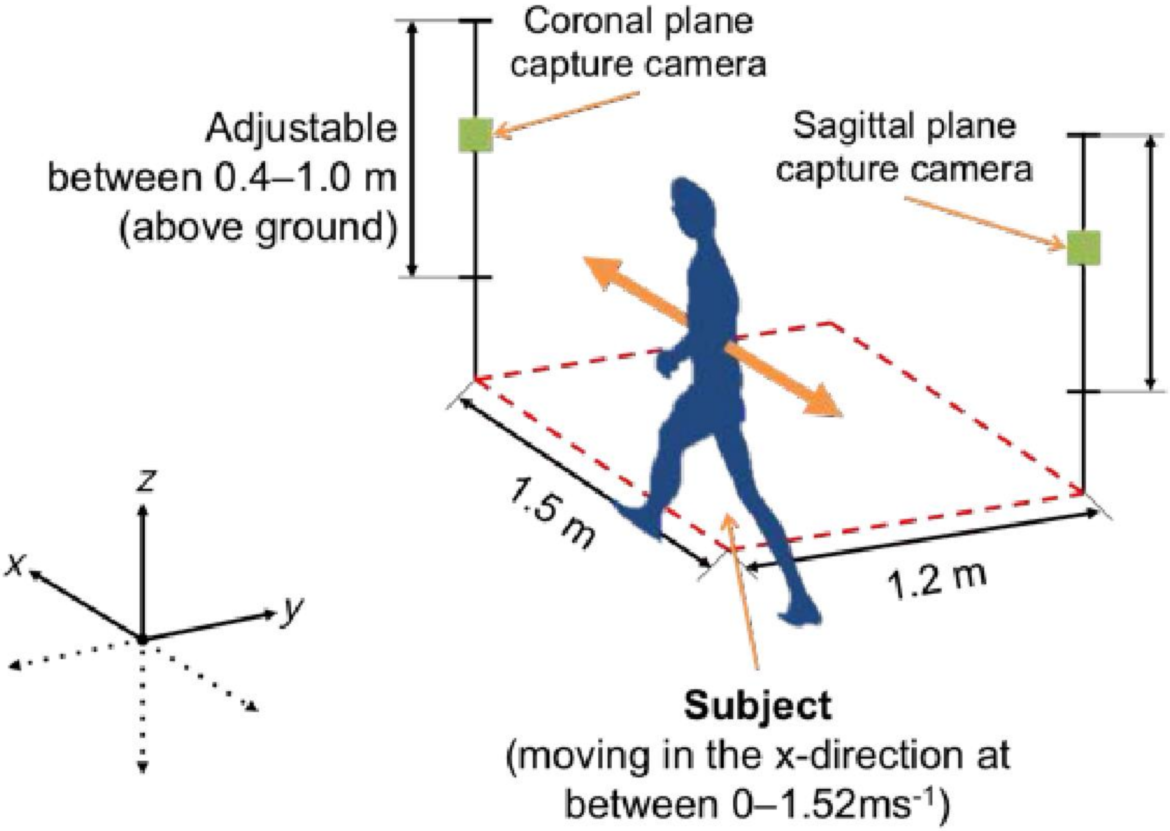


Figure 3.1: A simplistic visual representation of the specifications that must be abided by during the design phase of the GaitScanner. (Adapted from Schultz 2015)

A key requirement was that the GaitScanner must not impede patient gait. In order to successfully satisfy this requirement certain functions including motor speed and structural dimensions for the device were selected by using the basic gait temporal parameters as a constraint. All of the human gait constraints are represented in Figure 3.1. Using the average step length of 0.75 – 0.80 m and thus, an equivalent stride length of 1.5 m the gait depth allowance was set to this value. This would assure that the user of the device would always remain at approximately one stride distance away from the device. An adjustable height of at least 0.6 m was to cater for all of the different heights of the users, while still having the optimum height to record the camera footage.

4.

Conceptualisation

The conceptualisation phase takes all of the requirements and specifications identified in the previous chapter and uses them to help design concepts or develop possible ideas that will lead toward the final proposed device. The conceptualisation process is used as a tool to help start the design process which does not necessarily have to represent the final product. By detailing the physical implementation process, it provides a means of easily evaluating and assessing the aspects that need further improvement. Furthermore, as discussed in Section 1.2.3, an iterative approach was taken for this project. Consequently, the early concept designs were critical for creating the basis of which the final design was adapted from. This chapter outlines the conceptualisation process for the three project components identified in Section 3.2.

4.1 Device Structure Conceptualisation

The structure of the device is first aspect of the overall design that was addressed. The initial step before creating new ideas and concepts was to perform a comprehensive review on the current status of the structure. Once the key areas that were executed both poorly and well have been identified, the areas that require improvement can enter the conceptualisation process. This was undertaken using a two-step process focussing on the development of the enclosure followed by an ideation of different structural support mechanisms.

4.1.1 Current Structure

The current structure, shown in Figure 4.1, served its purpose to aid the GaitScanner device to succeed as a viable proof of concept. When generating ideas for a robotic device there are often a plethora of options which can be used to achieve the desired outcome. However, many of which become unfeasible due to limiting factors such as cost, ease of implementation and safety. This structure and primary locomotive method was designed with four key factors in mind; namely **simplicity**, **increased stability and smoothness**, **cost** and **use on indoor and outdoor surfaces**.

Figure 4.1: GaitScanner CAD assembly of previous structural design

Seeing as the client only intended to use this device for analysing straight line motion, wheeled actuation was the simplest option and would not cost a phenomenal amount of money to implement such that any budget constraints would be met. Another important factor was to ensure the structure had a stable base for the cameras to attach to, in order to capture and record smooth footage without the need for additional camera stabilising equipment. The final design incorporated a total of eight wheels to ensure the device was capable of traversing a variety of both indoor and outdoor surfaces.

Although the device has 8 wheels only one is powered connected to the motor located in the centre of the front section, while the remaining 7 wheels' act purely as rollers to help maintain the straight trajectory when in motion. This is a very intuitive design that not only minimises the cost but keeps the total number of active components to a bare minimum.

4.1.2 Structure Enclosure

A major component of the project is to create an enclosure for the current structure. The purpose of the enclosure is to protect and cover all of the exposed electronic componentry. While the current design was a practical means to gain quick access to the hardware, it is not suitable to be used in a clinical environment; the exposed componentry is shown in Figure 4.2.

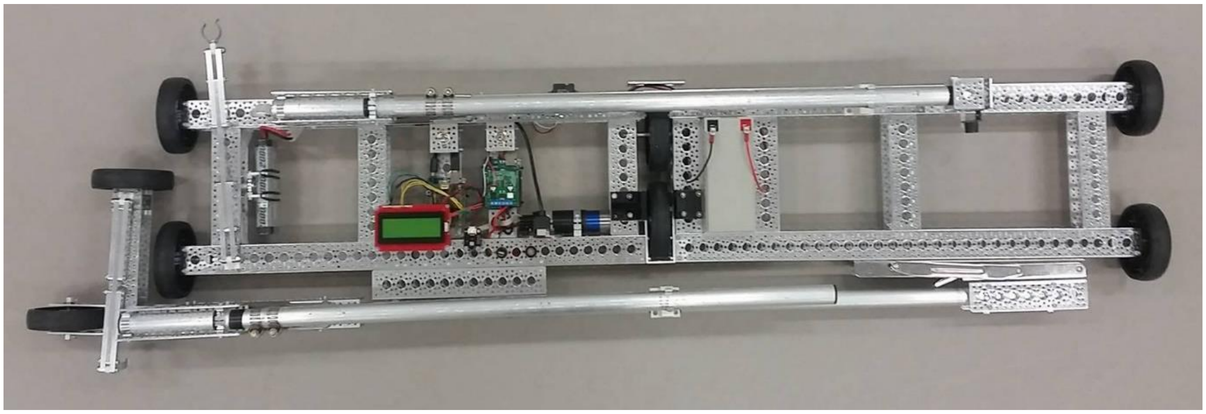


Figure 4.2: Compact view of previous GaitScanner with no enclosure.

The enclosure must consider and address the following:

Safety

The safety to the users of the device is paramount to the overall design. The electronic hardware must be protected from and possible damage and there must be minimal risk to the users of the device (i.e. sharp edges or pinch points etc.).

Ease of access

Not only must the enclosure cover any exposed componentry, it must also provide a suitable method of accessing the very same hardware the enclosure set out to cover. While the majority of the components will remain untouched after installation, the batteries and logic boards will need to be accessed for charging and writing new code respectively.

Aesthetics

The enclosure must take inspiration from existing medical devices such that the final prototype will look and feel like a regular medical device found in the clinical environment. While the aesthetics will not benefit the function of the design itself, a sleek non obtrusive design will help the subject to perform a natural gait cycle when using the device.

4.1.3 Design Process

Before any serious design or development can take place, it is crucial that a solid design process is outlined. For this project a 3 phase iterative process, shown in Figure 4.3, was identified as the best option for generating a suitable enclosure for the GaitScanner.

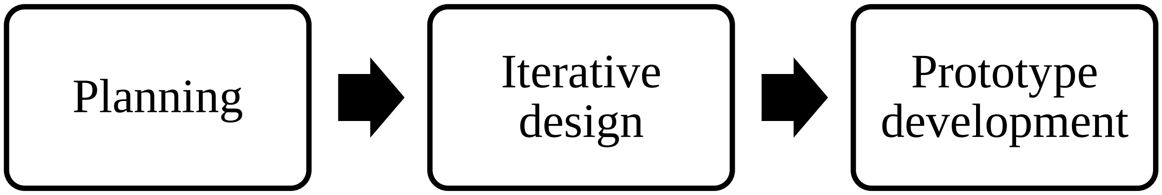


Figure 4.3: Design process for enclosure broken down into 3 key phases

Planning

The initial phase of the design process involves the planning of the listing and identifying of possible features and materials that may be beneficial to final design of the enclosure. The planning phase is required to form the foundation of each subsequent design, so to ensure that the design has solid foundations it will be necessary to study the features and characteristics of existing medical equipment such that the final enclosure of the GaitScanner resembles that of a medical device.

Iterative design

In the iterative design phase, a design is created using the initial background and planning as a reference. This design is then reviewed against the requirements of the project to identify any areas of improvement. A new design incorporating the appropriate adjustments is then made. This process of design and refinement is repeated until no further adjustments need to made in order to completely satisfy the requirements for the project.

Prototype development

Once the iterative design process has been complete such that it satisfies all requirements the design can exit the conceptualisation stage and enter prototype development which involves the physical construction of the GaitScanner prototype. This prototype development is detailed and documented in Chapter 5. Prototype Development.

4.1.4 Initial Prototype

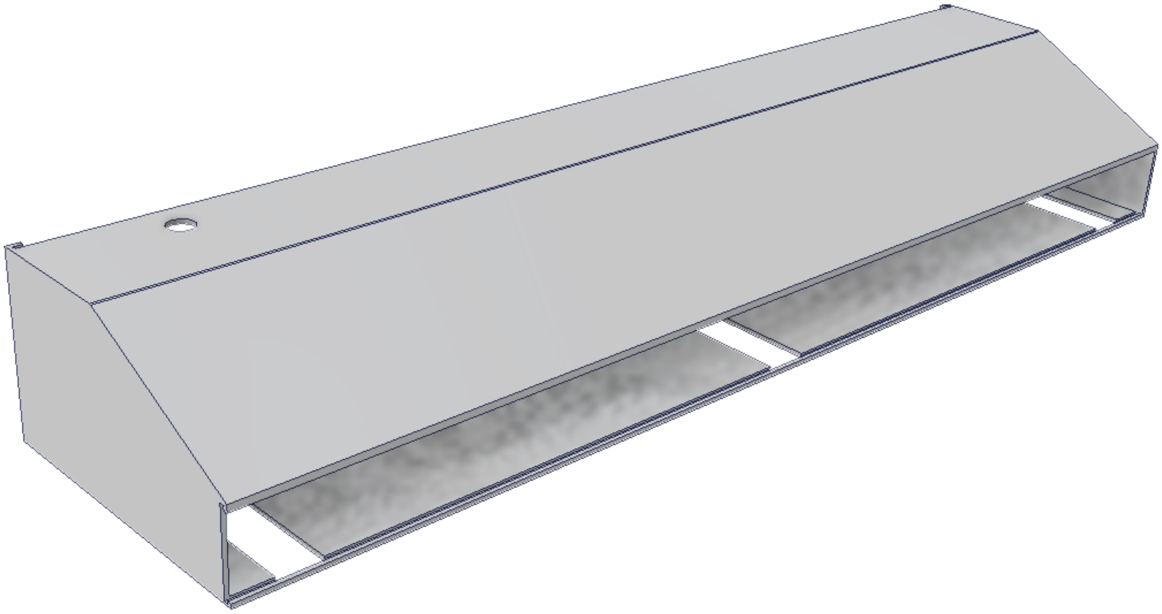


Figure 4.4: Initial prototype design for structure enclosure.

With a few basic considerations identified an initial 1st prototype enclosure design for the device was created, see Figure 4.4. The width of the enclosure spanned the entirety of the current device such that the current structure could sit inside with little construction required. The front panel was designed to be detachable in order to cover the straightener arm whilst in the compacted form but also to allow for full extension when the device is ready for use.

While the 1st prototype serves the primary purpose of acting a cover to the exposed componentry, specifics of the key areas including safety, ease of access and aesthetics must all be formally addressed. This initial prototype was designed to allow for the current frame of the Gaitscanner to be attached to the inside of the structure. However, if this were to be manufactured the total weight of the device would increase significantly making it much more difficult to transport.

Furthermore, it can be seen in Figure 4.2. that the electrical componentry used in the device only consumes approximately half of the allocated space with the remainder of the structure comprised of vacant space. Although it made use of a collapsible arm the width of the was fixed at 1.2 metres, which was identified as the optimal distance for camera placement. This distance however, is only required when the GaitScanner is in operation, thus the theoretical footprint of the device when not in use can be reduced.

Figure 4.5: A variety of different portable medical devices used as inspiration for conceptualisation of the new GaitScanner prototype.

The aesthetics are important to the overall success of the GaitScanner as a medical device. In order to develop a design suitable for a medical workspace it was critical to develop an understanding and envisage the current styles used in portable medical devices. After looking at a range of medical devices (Figure 4.5) it was evident that all modern medical devices strive to promote simplistic, clean and welcoming characteristics. The concepts and notions from existing medical devices can be used to help form the basis of further iterations of the prototype design.

4.1.5 Further Structural Considerations

Before the design of an official prototype can begin, it is beneficial to identify the possible types of fittings, connections and materials that may be used for the final construction of the prototype device. By constructing a general plan and having a greater understanding of the assembly process, the design of a prototype can be conducted in a more efficient manner.

4.1.5.1 Fittings and connections

To incorporate a greater degree of portability into the GaitScanner, the structure must make use of intelligent fittings which satisfy the maximum required dimension while also providing the ability to reduce the overall footprint of the device for transportation and storage purposes.

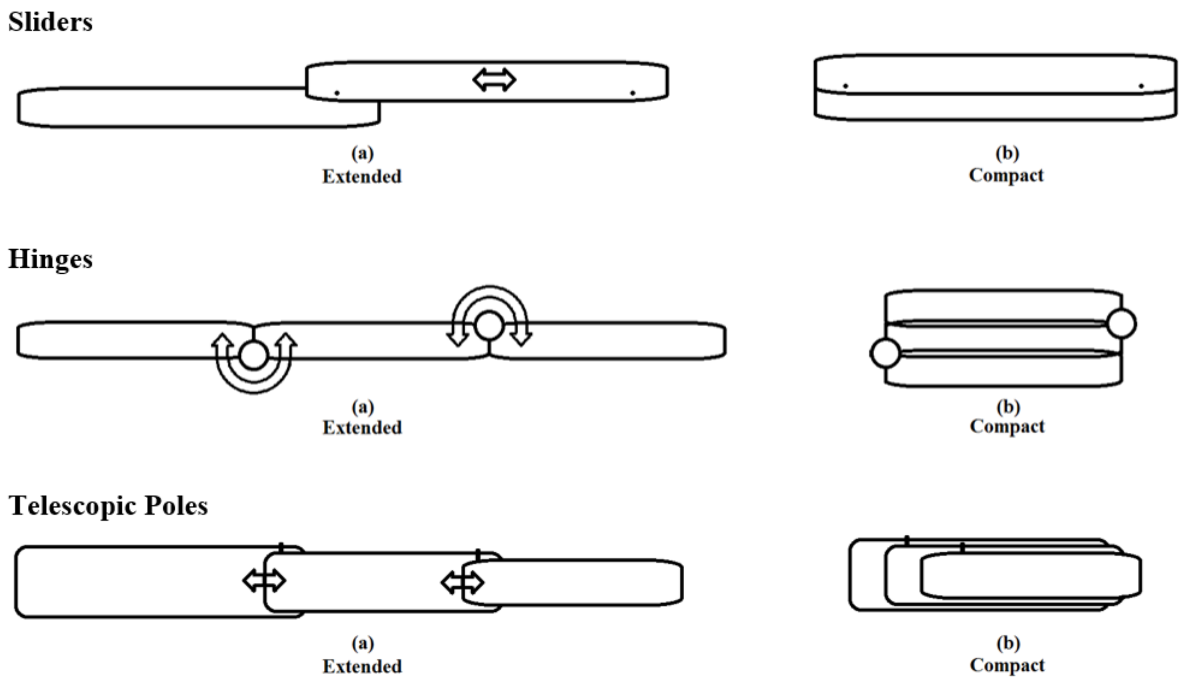


Figure 4.6: Cross sectional diagram of a slider, hinge and telescopic mechanism detailing both (a) extended and (b) compact views.

Three different methods shown in Figure 4.6, could be implemented to decrease the overall size whilst still providing the recommended operating lengths include sliders, hinges and telescopic systems. These systems could be implemented to replace the single hinged leg of the existing GaitScanner prototype. While all three methods appear viable, factors including ease of implementation and structural integrity must be satisfied of which can be verified through the CAD modelling process.

4.1.5.2 Materials

Choice of material is an important decision that must be made before beginning the construction of the new prototype. Although the GaitScanner is not intended to be a load bearing device, the materials used must still be able to withstand low intensity load for protective purposes yet be light weight and must be affordable.

The current prototype is primarily constructed of aluminium square bars, which served as a relatively strong and lightweight material that was easily utilised. However, the major concern using the square bars was primarily due to the overall appearance. The look of the aluminium gave the GaitScanner an industrial aesthetic compared to common medical devices. There are a few other alternatives that can satisfy the projects' requirements, these include acrylic (Figure 4.7) and 3D printed plastics.

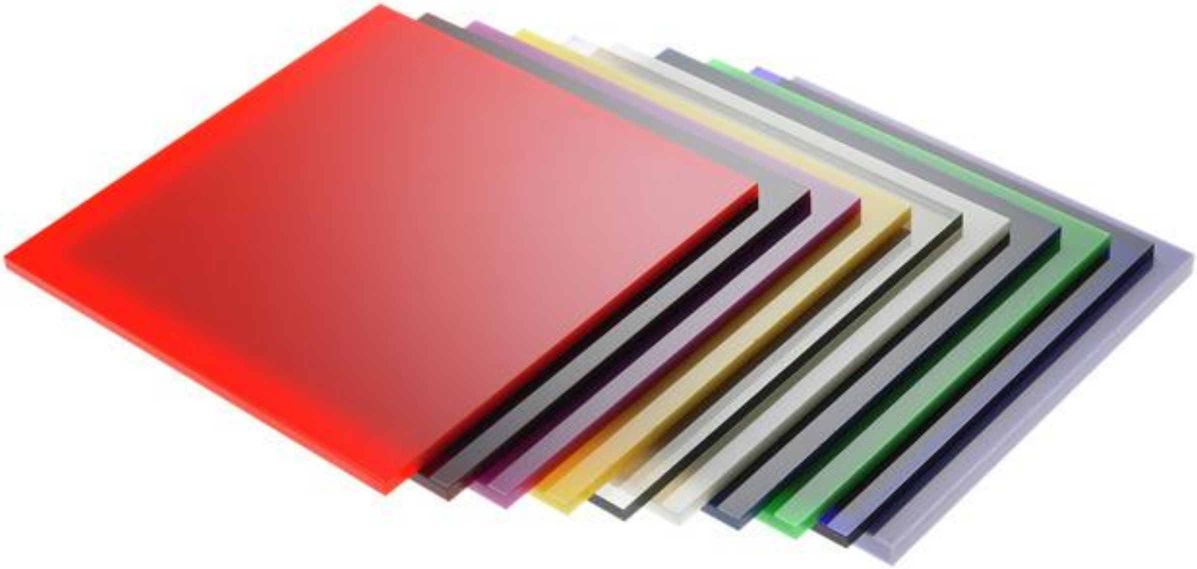


Figure 4.7: Example of acrylic sheets in a variety of colours.

Acrylic is a versatile material that can be precisely cut into specified dimensions using a laser cutter or bent using a vacuum former. The clean finish of acrylic eliminates any need for paint and its versatility allows it to be used in a range of situations including primary structural support or solely for aesthetic purposes. Another other option is to 3D print certain components that would otherwise require costly manufacturing such as injection moulding. The cost of 3D printing is calculated based on the overall volume of the material required for the print, such that it will be important to optimise any CAD designs to ensure the most cost efficient outcome. To ensure that the printed components are structurally sound the percentage of infill can be increased to give the maximum strength and stability.

4.1.6 Revised Prototype Design

The initial prototype design, while functional, did not resemble a medical device. As such it was important to incorporate some design elements and feel from currently available medical devices. Figure 4.8 shows the initial revised enclosure design incorporating a curved top rather than the prism box shape. This design, while evidently more streamlined than the last, was still the full length and did not present any opportunities for further compactibility of the device. In addition to the lack of compactibility, the enclosure was still intended as a direct cover that would allow the entirety of the current aluminium frame to fit inside. Although, by designing an enclosure that allows for the current structure fit directly inside without much alterations will save time and resources, the negatives far outweigh the positives. The size of the enclosure will add much unnecessary weight and it limits the size of the GaitScanner to the existing frame dimensions. For these reasons it was decided that in order to increase the utility of the GaitScanner it was vital that the enclosure made use of the current electronic componentry while eliminating the rigid aluminium frame.

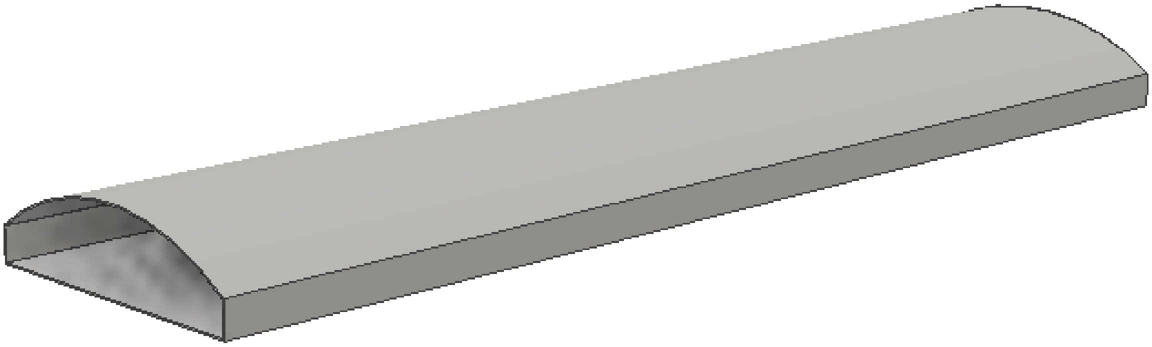


Figure 4.8: 1st revision of enclosure design.

In Figure 4.9 it can be seen that the electronic hardware consumes approximately 60% of the width, with the remainder of the structure vacant and used only to provide the required 1300 mm width for operation. With some thoughtful component placement, the hardware can comfortably occupy a 500 mm space increasing the possibilities of compactibility when the GaitScanner is not in use. The only limitation regarding size is that the GaitScanner is capable of expanding to the necessary operating dimensions of 1500 mm x 1300 mm for appropriate camera placement. The GaitScanner operates with a single driving wheel and seven rolling wheels, to ensure that the device travels in a straight line the motorised wheel must be positioned directly in the middle of the structure.

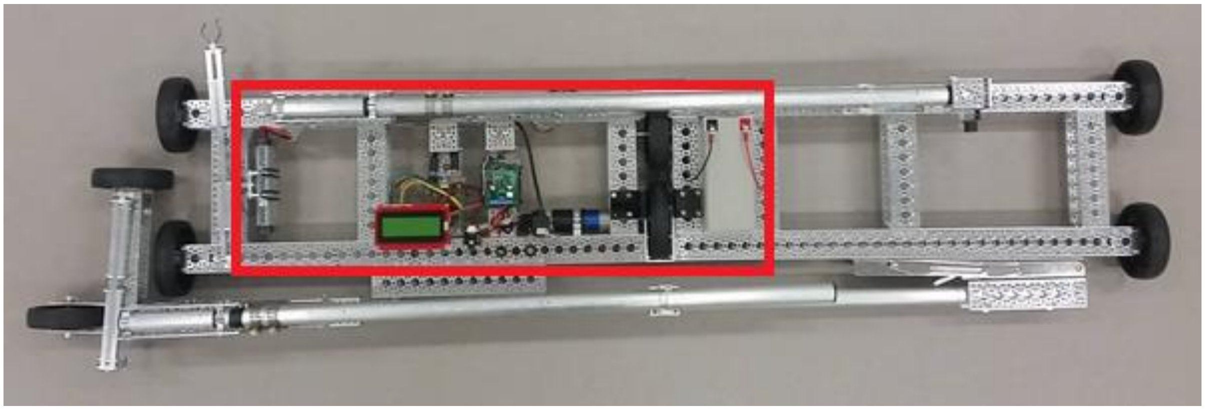


Figure 4.9: Current GaitScanner prototype with hardware space highlighted by red box.

In the initial conceptualisation phase different connections and fittings were identified, these included hinges, sliders and telescopic poles, all of which could be applied to decrease the compact size of the GaitScanner while providing the necessary expansion when needed. A final enclosure size of 650 mm was used and a slider mechanism was employed for the updated design, as shown in Figure 4.10.

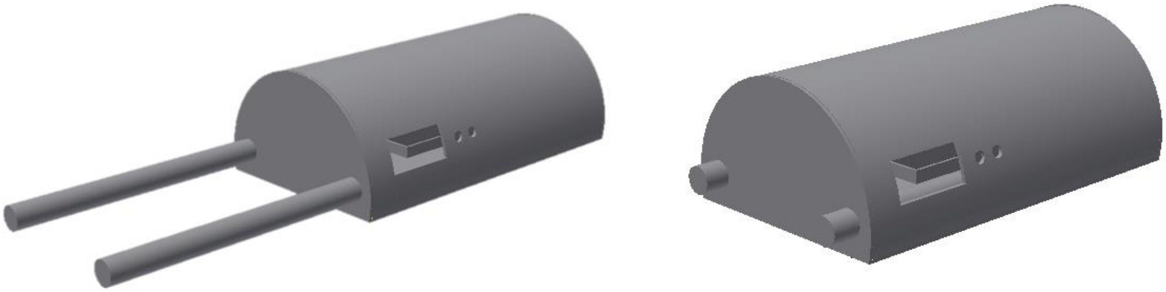


Figure 4.10: Enclosure design showing the possible collapsibility with the use of a sliding mechanism.

The revised design utilises aluminium rods which are attached to individual sliding mechanisms that are concealed on the inside of the enclosure. All of the electronic components are housed within the dome shaped design and the LCD screen and power switches can be fitted onto the face of the dome, with the cut out sections representing the proposed locations. The extending rods also provide a location to which wheels can be installed on to as well as the location for the follower leg to be attached.

The following iteration of the enclosure must account for an access point to the hardware, the configuration of the follower leg support, wheel placement and the location of the upright mounting camera poles.

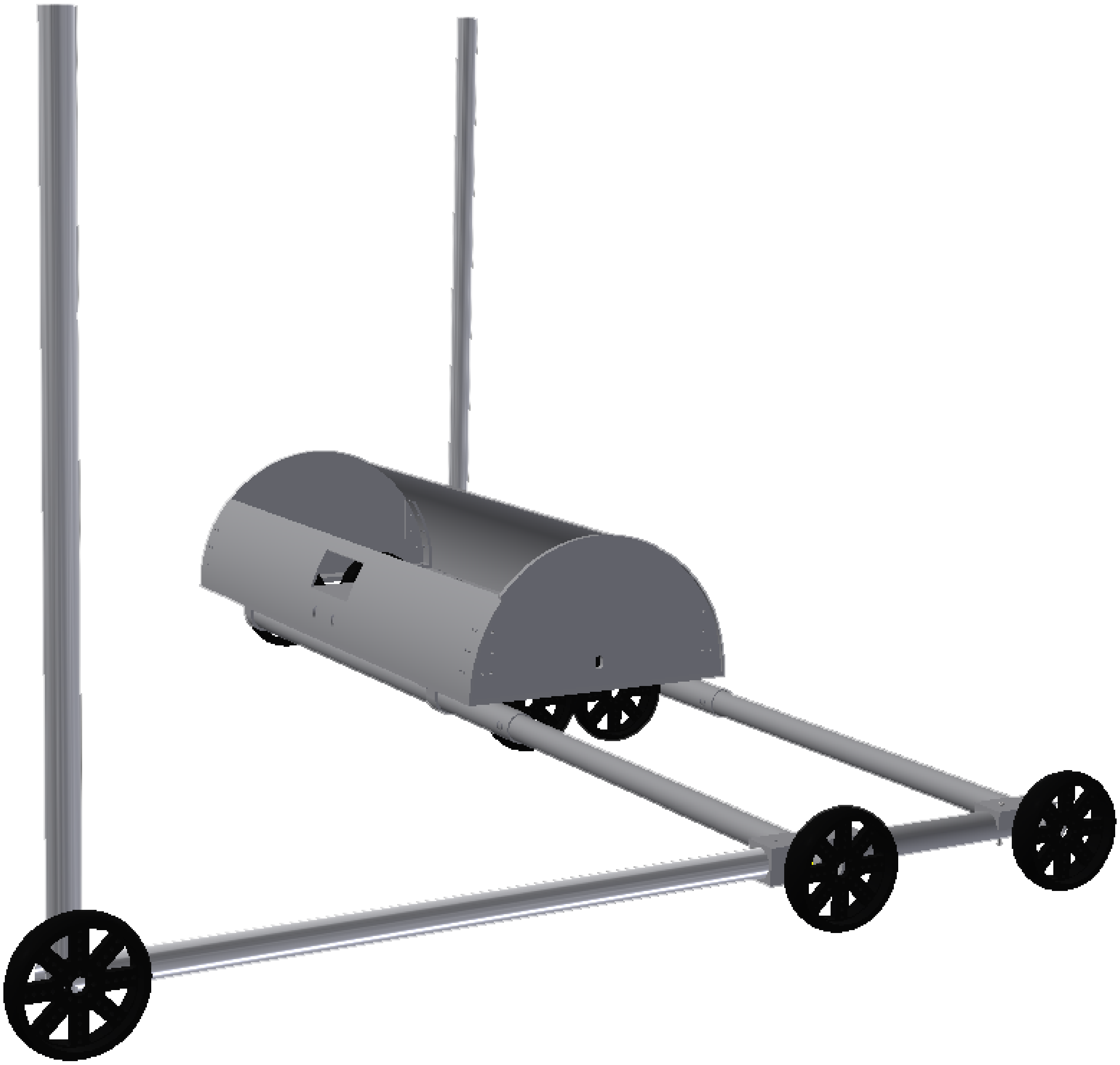


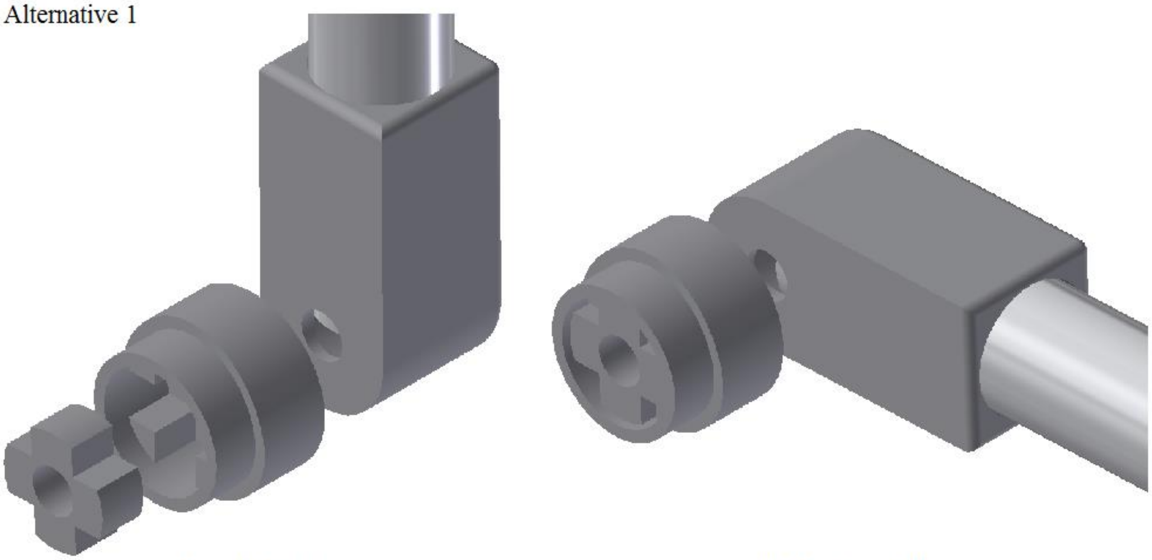
Figure 4.11: Third iterative design of enclosure prototype.

The third iteration of the enclosure retained the size and shape of the half cylinder while adding a lid for quick access to the inside of the structure, as shown in Figure 4.11. The sliding mechanisms were replaced with a telescopic pole configuration attached to the underside of the device to ensure all wheel axels were on the same level. The upright camera poles are attached using a 3D printed bracket that allows for the poles to rotate 90° in a horizontal position for when the device is not in operation.

The design of the telescopic pipes utilises a 28 mm diameter pipe coupled with an inner pipe with a 25 mm diameter. The poles will have a minimum maximum length of 1300 mm and a minimum length of 650 mm, giving the needed extra length to the GaitScanner during operation while also keeping the device as compact as possible. One alternative to making the telescopic poles is to use a camera monopod, which would provide a simple readymade solution. However, as a total of three telescopic poles are required (two attached to the main enclosure and one for the trailing arm) the cost will ultimately attribute to the final deciding factor.

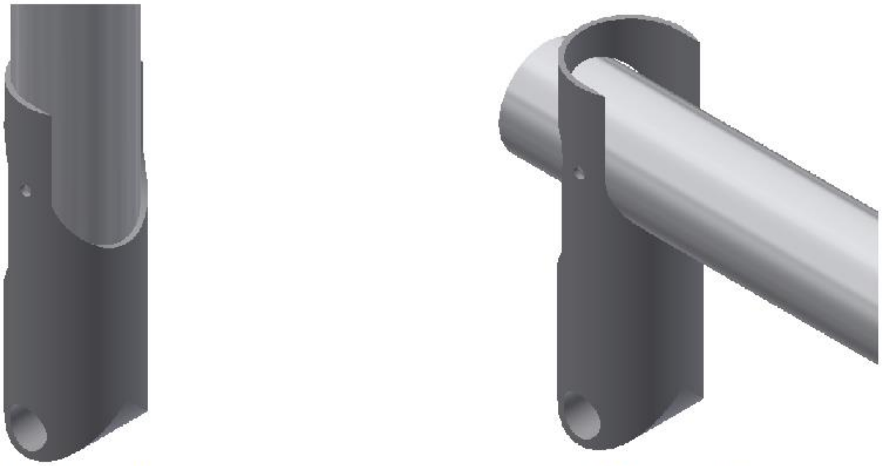
Two different designs have been considered for mounting the upright camera poles. The first design functions by using a plus-shaped lock mechanism and the second functions by using a pivot hinge. For the first design, the pole rotates freely 90° about a common axis and is locked when the plus-shaped nut pulled back to become engaged. The second alternative operates using a vertically translating pivot point, Figure 4.12 demonstrates a CAD model of both of the proposed mechanisms.

Alternative 1



(a) Upright Position (b) Horizontal Position

Alternative 2



(a) Upright Position (b) Horizontal Position

Figure 4.12: CAD model of upright camera pole mounting alternatives: displaying both (a) Upright Position and (b) Horizontal Position.

With the majority of the enclosure prototype design complete, the design process can continue to the next phase, which involves material and part acquisition followed by the prototype construction. The parts that will be reused include the following: batteries, motor, LCD screen, Arduino and wheels. All other necessary materials must be sourced prior to the construction of the device. The development of the enclosure prototype is detailed in Chapter 5. Prototype Construction.

4.2 Control System Conceptualisation

The control system was of major interest to the client as such it is of utmost importance that an appropriate approach is considered before altering the current controller design. The first stage involves quantifying the existing system to ensure a solid reference is available for validating and comparing any future improvements. Once the preliminary tests have been conducted, the different software and electronic componentry can be addressed.

4.2.1 Current System

The current control system operates using an ultrasonic proximity sensor to calculate subject distance, as the subject moves either forward or backward the GaitScanner travels accordingly to maintain a pre-programmed 145 cm distance. While this system performs adequately once the GaitScanner reaches a constant speed, it experiences significant delays upon acceleration and deceleration. This delay (or input lag) results in either an overshoot or an undershoot, which can affect the integrity of the recorded footage. In addition to the ultrasonic proximity sensor the GaitScanner has a front IR sensor for object and wall detection. The system has been programmed to come to a complete stop, overwriting all other commands, if anything is detected by the front sensor acting as an emergency stop feature.

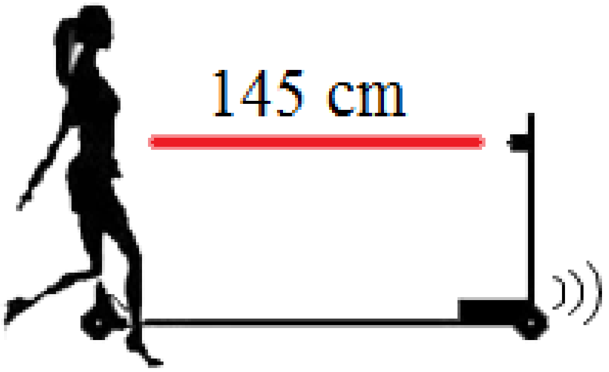


Figure 4.13: Diagram representing the pre-programmed 145 cm distance between GaitScanner and the subject.

Before altering the controller for the device the current control system must be scrutinised in order to identify the exact features and areas that require the most modification. The control system was put through a series of tests and trial scenarios, with speed, response time, alignment and stopping documented during each trial. The purpose of these tests are also to record the base values at which the device operated at prior to altering the controller, this creates a simple means of comparing and gauging any future developments of the control system. The GaitScanner has a secondary operating option whereby it travels either forward or backward at a predefined speed regardless of the subjects position from the sensor. This constant speed mode can be beneficial to the subject as it encourages them to maintain a specified speed. While this speed controlled mode does not rely on a PID system, it is still important to validate its accuracy.

The tests used to evaluate the control system included (all tests were conducted within a closed environment over a 20 m distance):

Test 1: Slow walk

The GaitScanner has been programmed to operate at speeds between 0 – 1.5 m/s which cover the typical walking speeds of post-stroke rehabilitation patients (reference). The slow walk was test involved operating the GaitScanner in the speed control mode at 0.75 m/s. The major concern during this test was that the GaitScanner deviated 1m to the left while travelling forward however, this could predominately be attributed to the lack of floor contact from the trailing guide wheel. Also due to the single front IR sensor the GaitScanner was experiencing difficultly detecting objects in front of the device as they were out of the sensor's field of view.

Test 2: Fast walk

The fast walk test increased the set speed to 1.25 m/s, which is closer to the upper limit of the system. Compared to the slow walk the GaitScanner travelled in a straighter trajectory at this faster speed however, like the previous test the front IR sensor did not perform adequately resulting in a small collision before initiating the emergency stop.

Test 3: Forwards/backwards walk

This test was conducted to analyse the PID controller's ability to track the subject when the GaitScanner transitions from a forward to a backwards trajectory. The GaitScanner experienced a small delay at the point of directional change, followed by an overshoot caused by the PID controller in an attempt to account for the delay before returning to the appropriate position.

Test 4: Walk to a stop

The final test was conducted to measure the time taken the for the GaitScanner to reach the 145 cm programmed distance when the subject stops walking. When the subject began to come to a stop the GaitScanner it took 10 seconds, oscillating above and below the steady state before reaching the 145 cm distance. The plot from this test is displayed in Figure 4.14.

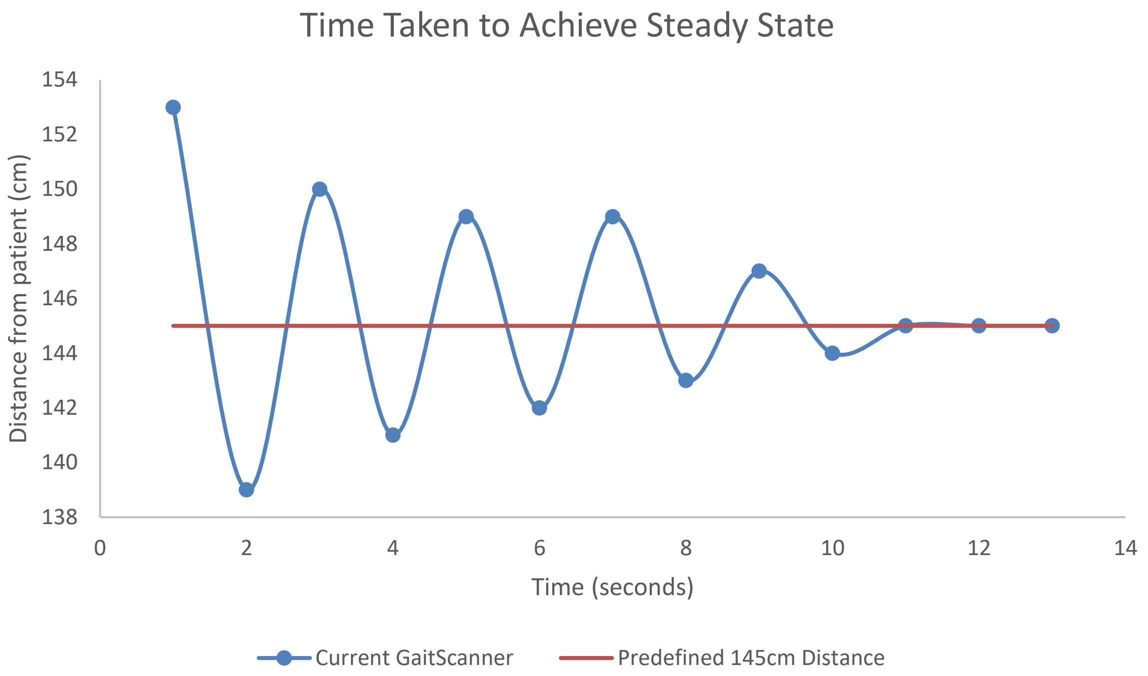


Figure 4.14: Plot representing the time taken to reach a steady state under specified testing conditions.

4.2.2 Improvements

After performing tests on the current GaitScanner control system the areas of improvement can be related to either the hardware or software. By addressing both the sensors and the PID control system the new prototype for the GaitScanner will have a multifaceted increase in accuracy and efficiency respectively.

4.2.2.1 Hardware

The GaitScanner was created using Arduino as the base platform, running off of two separate Arduino Uno R3 boards. The system relies predominately on the ultrasonic proximity sensor for subject detection alongside a single front IR sensor for object detection. After conducting the preliminary tests on the existing control system it was noted that the GaitScanner failed to stop when objects blocked the device. In all cases that the device failed to recognise these obstructions, it was due to the fact that the objects were not within the front IR sensor's field of view. In order to improve and rectify these detection issues the number of IR sensors should be increased to cover a broader sensing area. The updated coverage range for object/wall detection of the GaitScanner is represented by Figure 4.15.

Figure 4.15: A top down representation of the new object/wall detection coverage compared to the original prototype.

In addition to the front IR sensor, the other hardware upgrade that will significantly improve the performance of the device is the subject tracking sensor. The current GaitScanner prototype utilised an ultrasonic proximity sensor for detecting the subjects distance. The limitations of this sensor and concerns regarding its performance had been brought up in the towards the end of the project last year. Due to budget and time constraints no further action was taken regarding this issue however a comprehensive review of other sensing technology was made and a recommendation for a LIDAR sensor was given. Acting on this information different LIDAR sensors with simple Arduino integration were research and after deliberation with the university supplier the LeddarTech LeddarOne Optical Range Finder was selected, shown in Figure 4.16.

LeddarOne Optical Range Finder Specifications

- Accuracy: 5cm
- Data refresh rate: 100Hz
- Operating temperature range: -45°C to 85°C
- Distance precision: 6mm
- Distance resolution: 10mm
- Power consumption: 1.5W
- Interface: 3.3V UART
- Wavelength: 850nm
- Power supply: 5V

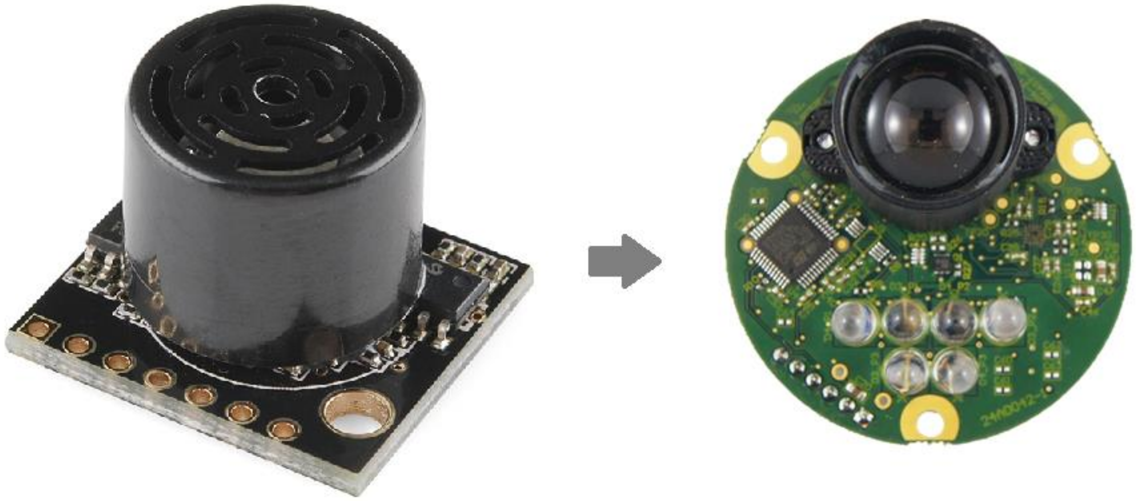


Figure 4.16: Sensor upgrade from Ultrasonic Range Finder to LeddarOne Optical Range Finder.

4.2.2.2 Software

While upgrades to the GaitScanner's hardware will improve the system performance, these alone however, will not be enough to satisfy the clients requirements. In order to fully realise the potential of the GaitScanner as a medical device, upgrades to the software, namely the PID control system, must be made. Section 4.2.1 detailed the control system for the current prototype and a series of tests were completed in order to evaluate the performance. From these test it was decided that a multiplier would be added the PID controller to account for the time delay upon acceleration and deceleration of the GaitScanner. The PID controller would effectively operate with a parameter increasing and decreasing multiplier depending on the subject's location with respect to the predefined set point distance. In the instances whereby the subject is at the prescribed distance of 145 cm the GaitScanner will operate under its default parameters. However, if the subject travels too fast or slow the control system will initiate a compensation tactic depending on the instance (Figure 4.17).

Instance 1: Subject < 145 cm

In instance 1, the subject is travelling faster than the GaitScanner's current speed. The control system will then activate a multiplier that promotes an aggressive output, greater than the standard parameters evoked by the default PID controller. The multiplier decreases as the subject returns closer to the 145 cm set point distance.

Instance 2: Subject > 145 cm

In instance 2, the subject is travelling faster than the GaitScanner's current speed. The control system will then activate a multiplier that promotes a passive output, less than the standard parameters evoked by the default PID controller.

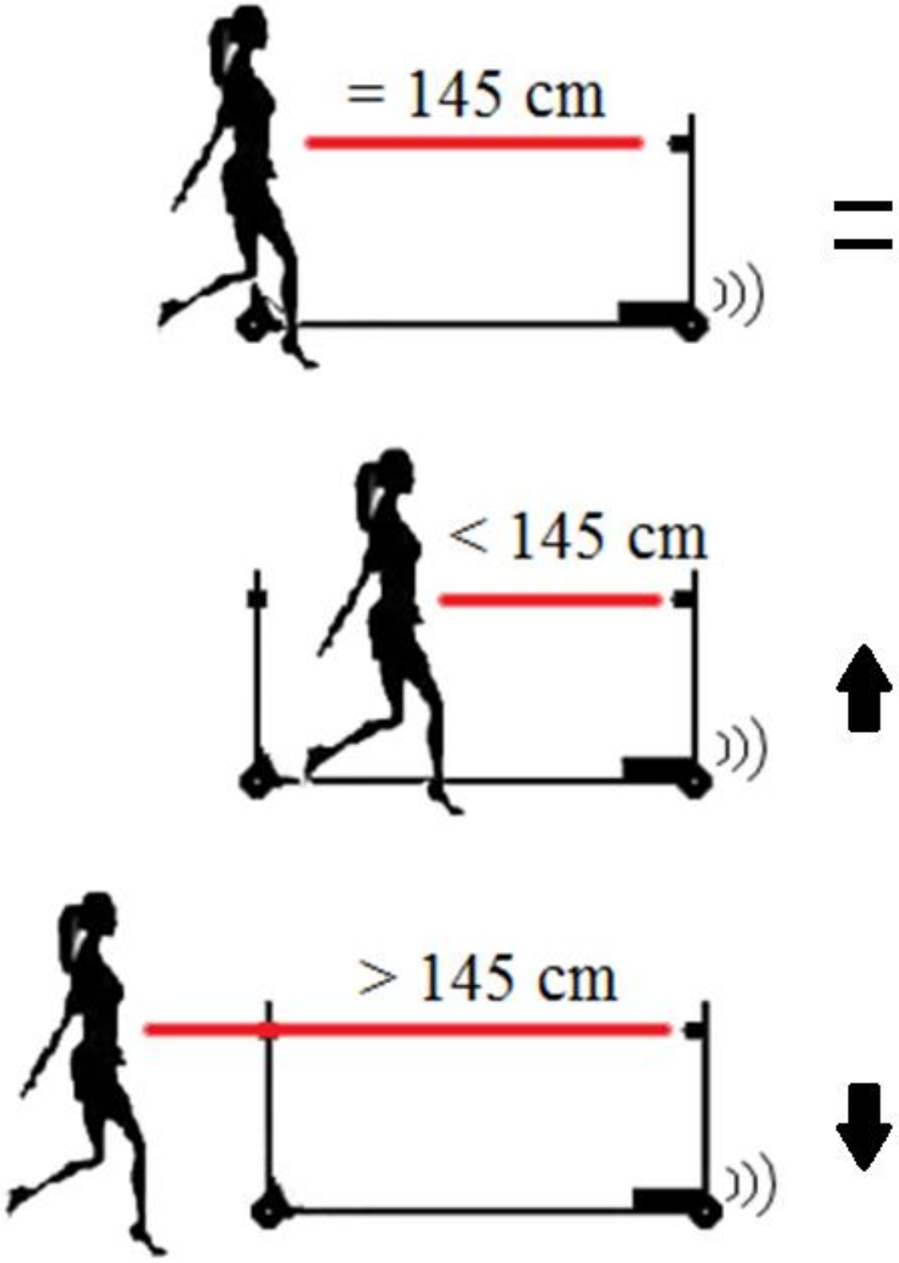


Figure 4.17: Diagram representing the proposed control system improvements. No change to PID parameters when subject distance = 145 cm (top), Increase in PID parameters when subject distance < 145 cm (middle) and decrease in PID parameters when subject distance > 145 cm (bottom).

4.3 Video Playback Conceptualisation

The final aspect of the project that must be considered is the means of video playback. In its current state there is no tailored program to accomplish this, thus the user is required to use any proprietary video playback program at their disposal to individually review the captured video footage. As such the primary role of the program is to have synchronous video playback of both view points from one subject trial. This would help a clinician analyse and monitor a subjects' condition without having to deal with multiple video windows and separate playback controls.

When creating any program, it is important to consider which features are necessary in order satisfy the basic needs of the program. While the desired outcome has been identified the platform to accomplish this must be considered. Initially C++, html5 and MATLAB were all considered as possible platforms to create this program however, due to its inbuilt functions and previous experience, MATLAB was selected.

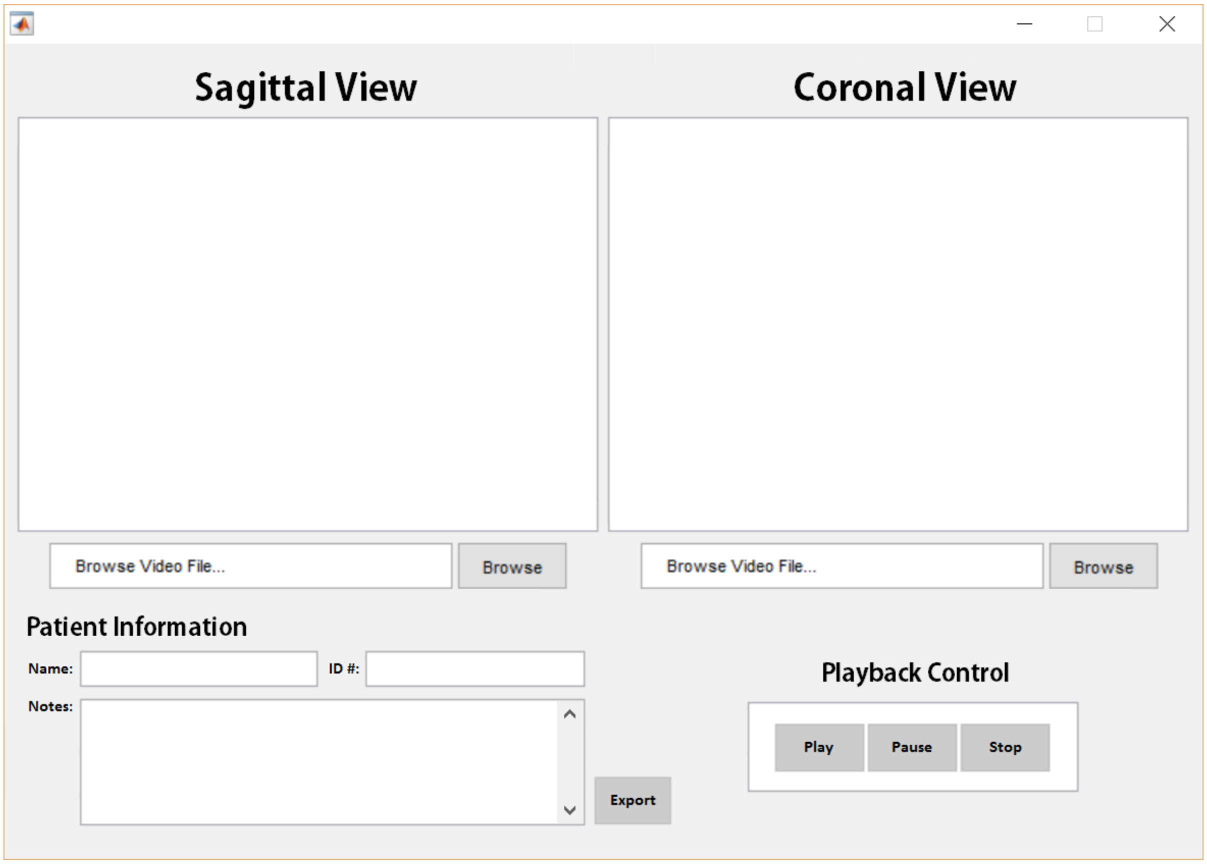


Figure 4.18: *Mock GUI for video processing program edited using Adobe Photoshop Elements 13*

4.3.1 Program Features

Before beginning to code the program a mock GUI was developed using *Adobe Photoshop Elements 13*, as shown in Figure 4.18. The purpose of this mock GUI was to help visualise all of the features that will encompass the program. Consequently, this initial concept is solely a representation of what the final program hopes to achieve and the placement of any text, frames or buttons will not necessarily represent the final program. The following subsection details the features and describes their overall purpose to the program.

Parallel Video Display

The major feature of the program will be the parallel video display. This allows both of the captured footage from the sagittal and coronal views to be reviewed simultanneously. Being able to view the footage from both anatomical planes, clinicians will be better equipped to make a diagnosis' or monitor a subject post capture.

File Explorer

The videos are stored on the internal storage of each respective GoPro camera and can be accessed when they are connected to a computer. The file explorer feature will allow the user to load the video files directly from the interface of the program.

Video Controls

The single set video controls allow both of the videos to be controlled simultaneously. Three buttons, pause, play and stop are all that is required for basic video control as such the program has adopted this simplistic approach.

Patient Information

The client intends to use this device for patient trials in a full capacity with an upwards of 20 subjects per day. In order to keep a record of each patient, basic information can be entered in the supplied text fields. In addition to the patient information, any key characteristics or events that that occur during the video can be recorded in the notes section. By incorporating a text field directly into the video playback program it eliminates the need to have multiple windows open displaying different applications, ultimately providing a more complete user experience.

Export to File

The export to file feature takes all of the data that has been entered into the patient information text fields and exports it to a text file. This allows the user to create a log of subject entries that can all be accessed at later dates which is beneficial when monitoring the progression of a condition or the improvement of rehabilitation etc.

4.3.2 Other Considerations

Before implementing any of these concepts for the video playback program there are other important area that must be addressed. A major issue concerning the viability of the parallel video playback is the issues regarding synchronicity between the two videos. The other area to address is the method by which the recorded videos are transferred from the cameras to a computer ready to be imported into the program.

Figure 4.19: GoPro Smart Remote (image courtesy of GoPro)

Video Synchronicity

In order for the parallel video feature along with the synchronous playback, it is important that both the sagittal and coronal views have a common starting timestamp. This is to ensure that each frame of both viewpoints are referring to the same point when reviewing the footage. Currently, the user is required to simultaneously push both record buttons on each device or crop each video at a later date. Both of these techniques are not ideal as they are cumbersome and very inaccurate. However, a simple solution to this problem exists, namely the GoPro Smart Remote (Figure 4.19). The GoPro Smart Remote allows for up to 50 cameras to be controlled simultaneously to record synchronised video. This solution is the most practical option and will not affect the integrity of the GaitScanner device.

Video Transfer

In order for the program to playback the footage, the recorded video files must be transferred or the cameras must be connected to a computer. There are three different ways this can be accomplished. The first is to connect the both GoPro cameras to the computer directly using a mini USB cable. Similarly, the second method involves connecting the micro SD card to a card reader or USB adapter. The final method of video transfer is through wireless communications. The GoPro cameras each have their own Wi-Fi network which a computer can connect to. Once connected to the camera the files can be transferred wirelessly through a network connection. Understanding the multiple methods of video transfer will make navigating the program easier for the user.

Kinetic Foot Pressure Measurement Systems

The scope of this project focuses on recording qualitative video data and does not require a kinetic measurement system to be designed. However, there are third party devices which can be used in conjunction to bridge the gap, providing clinicians with additional kinetic data alongside the existing temporal parameters. The client has expressed his interest towards the commercial Moticon OpenGo device, which is packaged with proprietary software for extracting and analysing this data. While this does require a supplementary program it does broaden the overall function of the GaitScanner which may help generate appeal to a wider clinical base if seamless integration can be established.

5.

Prototype Development

The final prototype for the GaitScanner was constructed by combining the design specifications with the concepts and ideas formed in the previous chapter. This chapter focuses on the final design and the acquisition of materials prior to construction. The following section details the process of the how the GaitScanner prototype was constructed and how specific weaknesses of the design were overcome. The addition of a new sensor and improved control mechanism are then described. This chapter concludes by explaining the process involved to develop the video playback GUI for post processing the recorded GaitScanner footage.

5.1 Final Prototype

Please note that in future, if the GaitScanner is to enter the market and is produced on a larger scale the material selection would be governed by different parameters. While the function would remain the same, the materials would be altered accordingly.

5.1.1 Materials Selection

When deciding on what materials to use, it was important to remember that the materials must be lightweight, cost appropriate, readily available and easy to manipulate, as this prototype was to be constructed solely by the tools available at Flinders University. The previous prototype was constructed entirely from aluminium materials, although its lightweight characteristics and strength properties are ideal, visually it does not resemble a medical device. Other suitable alternatives that were not considered, due to cost and complexity included carbon fibre, titanium and various injection moulding techniques. Ultimately, it was decided that aluminium would be the ideal material to construct a frame. However, in order to keep aluminium visibility to a minimum an alternative material must be selected for the primary enclosure component. In Chapter 4 Conceptualisation, materials including acrylic and 3D printed plastics were identified as possibilities to be used as the primary material. After further thought into the possible materials, PVC was identified as a great alternative due to its cost, availability and shape. All of the conceptualised prototypes featured a cylindrical shape, which would require heavy manipulation to achieve if a material such as acrylic was to be used. PVC however, is readily available as a pipe of varying diameters and could be utilised directly in the prototype design with minimal difficulty. The following materials were selected as the primary choices to be used in the construction of the GaitScanner prototype.

PVC Pipe

A PVC pipe of 250 mm outer diameter with a 6 mm wall thickness was the largest commercially available diameter at a 1m minimum length. The final design needed to be altered to incorporate the PVC pipe as the primary enclosure component.

Aluminium

The support frame of the prototype will be made using aluminium tubing, its great structural and material properties make it well suited in these situations. It is readily available in a variety of diameters and lengths and can be source locally at a competitive price point.

Acrylic/3D printed plastic

Although acrylic and 3D printed materials will not be used in a large scale capacity, they will be ideal for any smaller components such as mounting panels and wheel brackets etc. as they can replicate the CAD models to high accuracy and in a rapid timeframe.

5.1.2 The Design

Figure 5.1 is a labelled diagram of the final design prototype of the GaitScanner. The following section details each main component and the material it is constructed from.

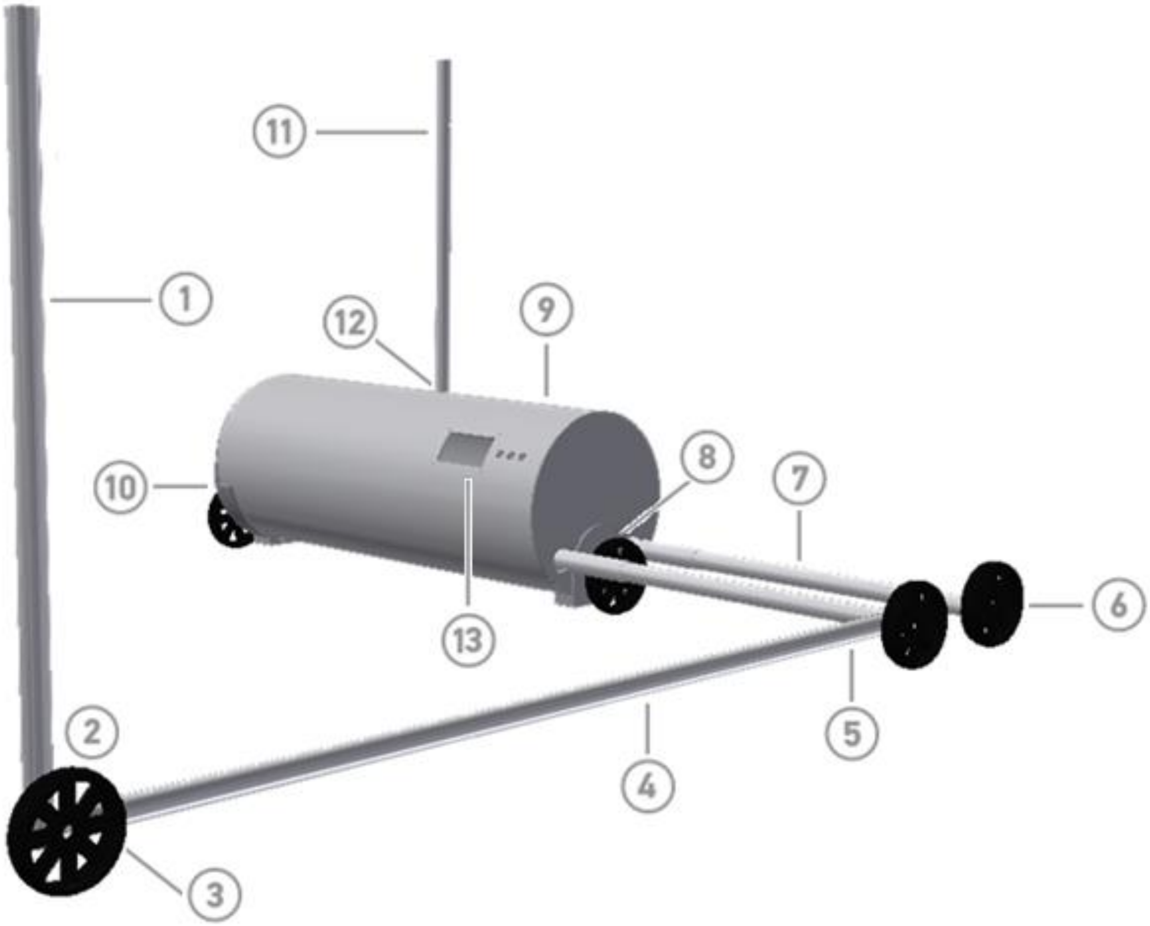


Figure 5.1: Labelled diagram of final design prototype.

1. **Sagittal upright**

   The sagittal upright is a 1m aluminium pipe with a 25 mm external diameter. A camera is then able to mount at any position along the pipe, capturing stable footage of gait in the sagittal plane. The sagittal upright is secured in a purposefully designed hinge.

2. **Sagittal upright hinge**

The upright hinge (used by both sagittal and coronal upright poles) is a 3D printed attachment that is designed to allow the upright pole to rotate 90° in a clockwise direction. The hinge itself is fixed to the three tier extendable arm, which is connected to the rear wheel bracket.

3. **Rear wheel**

   The 4-inch diameter rear wheel is connected to the end of the three tier extendable arm using a 3D printed custom made attachment. The wheel is fixed parallel to the direction of motion and rolls freely on ball bearings. The primary function of the is wheel is to help the GaitScanner maintain a straight trajectory during operation.

4. **Three tier extendable arm**

   The three tier extendable arm has a maximum length of 1.2 m and a minimum length of 0.8 m. The arm utilises aluminium pipe of varying diameters in a telescopic mechanism with locking snap buttons. The outer most pipe has a 28.58 mm diameter, the middle pipe has a 25 mm diameter and the inner pipe has a 22.23 mm diameter. The role of this extendable arm is to connect the rear wheel and sagittal upright to the main body of the GaitScanner.

5. **Hinge**

   The hinge is responsible for connecting the three tier extendable arm to the main body of the GaitScanner while allowing for a 90° rotation in the clockwise direction. The hinge is constructed from a combination of a repurposed camera accessory along with 3D printed connectors. The hinge has a screw to lock the ball and socket joint into place once the extendable arm is in the desired position.

6. **Right side wheel**

   A pair of dolly wheels for the right side of the GaitScanner, these wheels are connected to the two tier extendable arms using a 3D printed mount.

7. **Two tier extendable arms**

   The pair of two tier extendable arms have a maximum length of 1.3 m and a minimum length of 0.65 m. The arm utilises aluminium pipe of varying diameters in a telescopic mechanism with locking snap buttons. The outer most pipe has a 28.58 mm diameter and the inner pipe has a 25 mm diameter. The pair of pipes are connected internally within the body of the enclosure.

8. **Centre wheel**

   The centre dolly wheel is attached directly adjacent to the internal motorised wheel; the wheel is connected using a unique 3D printed bracket that slides directly onto the enclosure PVC pipe.

9. **Main enclosure**

   The main enclosure is constructed entirely out of a 250mm diameter PVC pipe of 0.65 m length. The PVC pipe has a wall thickness of 6 mm that allows for the 3D printed wheel mounts to attach onto. The primary purpose of the enclosure is to protect and house the internal electrical components.

10. **Left side wheel**

    A pair of dolly wheels for the left side of the GaitScanner, these wheels are connected to the body of the enclosure using a 3D printed mount.

11. **Coronal upright**

    Identical to the sagittal upright the coronal upright is a 1m aluminium pipe with a 25 mm external diameter. A camera is then able to mount at any position along the pipe, capturing stable footage of gait in the sagittal plane. The sagittal upright is secured in a purposefully designed hinge.

12. **Coronal upright hinge**

    The coronal upright hinge is an almost identical component to the sagittal upright hinge, with minor adjustments made to the attachment method.

13. **LCD screen & power switches**

    The LCD screen displays all of the context menus and functions to help navigate the through the control system during operation of the GaitScanner. To the right of the LCD screen are the two power switches and a power notification light. These toggle switches activate the 12V and 7.2V batteries, giving power to the device. The notification light illuminates in a green colour to indicate the GatiScanner is receiving power from the batteries.

5.1.3 Prototype Construction

5.1.3.1 Disassembly of the Old GaitScanner Frame

The first stage of the prototype construction was to begin disassembly of the old prototype frame. The primary reason for disassembling the old prototype was to acquire any componentry that could be reused in the new prototype. The main area of interest was the electronics for the control system, the complete list of componentry is shown in Figure 5.2.

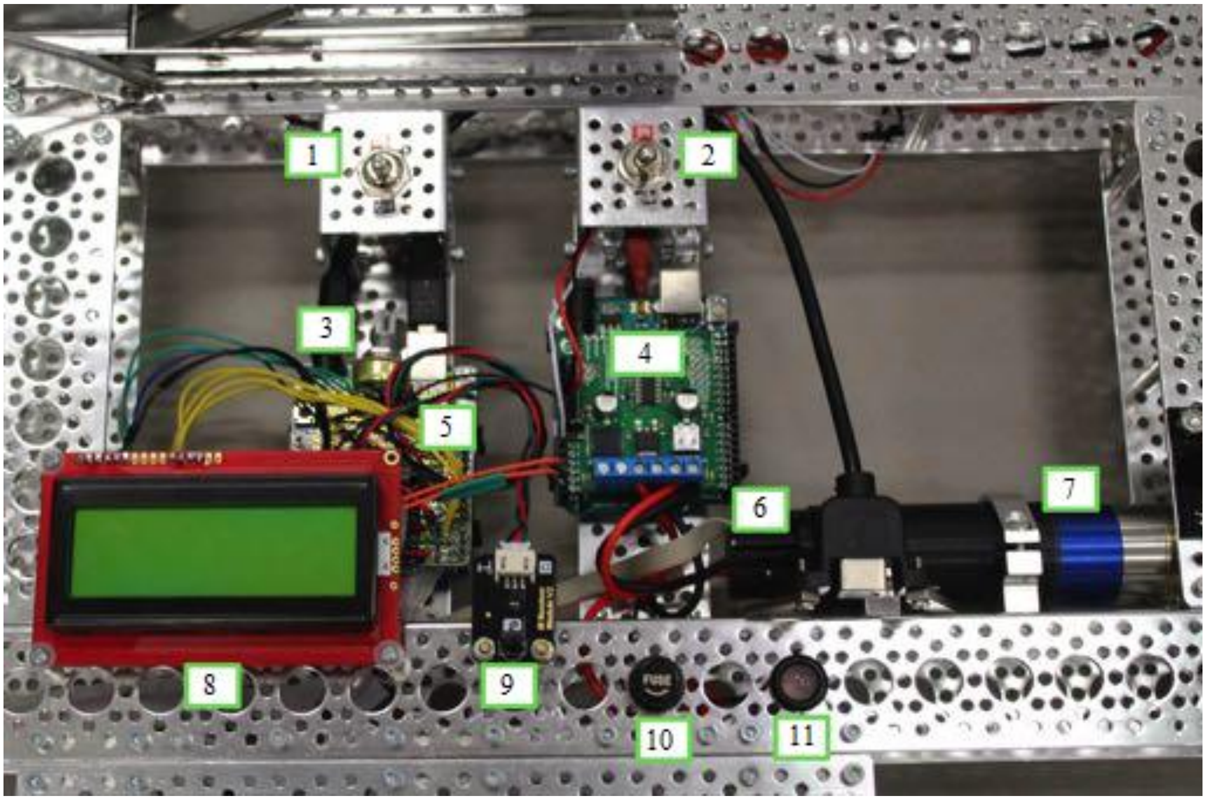


Figure 5.2: Labelled diagram of final design prototype.

1. Master Arduino power toggle switch
2. Slave Arduino / motor driver power toggle switch
3. Potentiometer to control LCD contrast
4. Motor driver, Slave Arduino
5. Master Arduino
6. Encoder
7. Motor and gear-head
8. LCD display
9. IR receiver (for remote control)
10. Current limiting fuse
11. Charge indicator
12. 7.2V and 12V rechargeable batteries (Not shown in diagram)
13. Ultrasonic proximity sensor (Not shown in diagram)
14. IR proximity sensor (Not shown in diagram)

The frame was held together with over 200 individual Allen screws; it was important that they were all removed with caution ensuring that the components could be uninstalled without any damage. In addition to the electronics the other components that were needed for the new prototype included the 25 mm aluminium tubing, wheels and their respective axels and bearings. Although the Actobotics aluminium channelling is not going to be reused for the new prototype, it is a relatively expensive material that should also be preserved for using any projects in the future.

5.1.3.2 Preparing the PVC & Aluminium Tubing

After all of the necessary components and materials were salvaged from the old prototype, the next step was to prepare the PVC pipe and aluminium tubing to the appropriate lengths. Figure 5.3 shows the PVC was cut to 650 mm in length with sections along the surface removed for the wheel, LCD screen, coronal upright hinge and the IR proximity sensor. The complete specifications for the PVC pipe can be found on the engineering drawing in Appendix B.

Figure 5.3: PVC pipe cut to specified dimensions.

The aluminium tubing needed for the new prototype came in three different diameters (28.58* mm, 25* mm and 22.23* mm *outer diameter) and was used to make the three tier extendable arm, a pair of two tier extendable arms and both the coronal and sagittal camera uprights. Table 5.1 summarises the different tube lengths and diameters used for each of the components.

Table 5.1: Summary of different aluminium tube diameters and their required lengths to assemble the necessary components.

Component	28.58 mm	25 mm	22.23 m
Three tier extendable arm	600 mm	500 mm	500 mm
Two tier extendable arm (x2)	700 mm	500 mm	N/A
Camera upright (x2)	N/A	1000 mm	N/A

All of the fabrication and machining work was completed professionally upon request, by the Engineering Service team at Flinders University. Once the aluminium tubing was cut to size, an 8 mm hole was drilled 100 mm from either ends of each aluminium section. A single end snap button was then inserted into the tubes and finally the tubes were then inserted into one another to form the final assembly of the three and two tier extendable arms. The snap buttons serve as a locking mechanism for the aluminium tubes when the desired length is reached, effectively making both the three and two tier extendable arms into functioning telescopic poles (Figure 5.4).

Figure 5.4: Three tier extendable arm (top) and two tier extendable arm (bottom)

5.1.3.3 3D Printing/Laser Cutting Components

During the conceptualisation phase of the project 3D printing and laser cutting was identified as a suitable method for creating and acquiring certain components for the GaitScanner. A total of eight components were designed to be 3D printed, these included six different wheel mounts and two camera upright mounts and the hinge connecter piece. The detailed specifications for each individual design can be found in Appendix C. An initial print of the components was made on a MakerBot Replicator 2 using a layer height of 0.3 mm and a 50% infill complete with full raft and support structures. Figure 5.5 shows a screenshot of 4 components on the MakerBot software ready for printing.

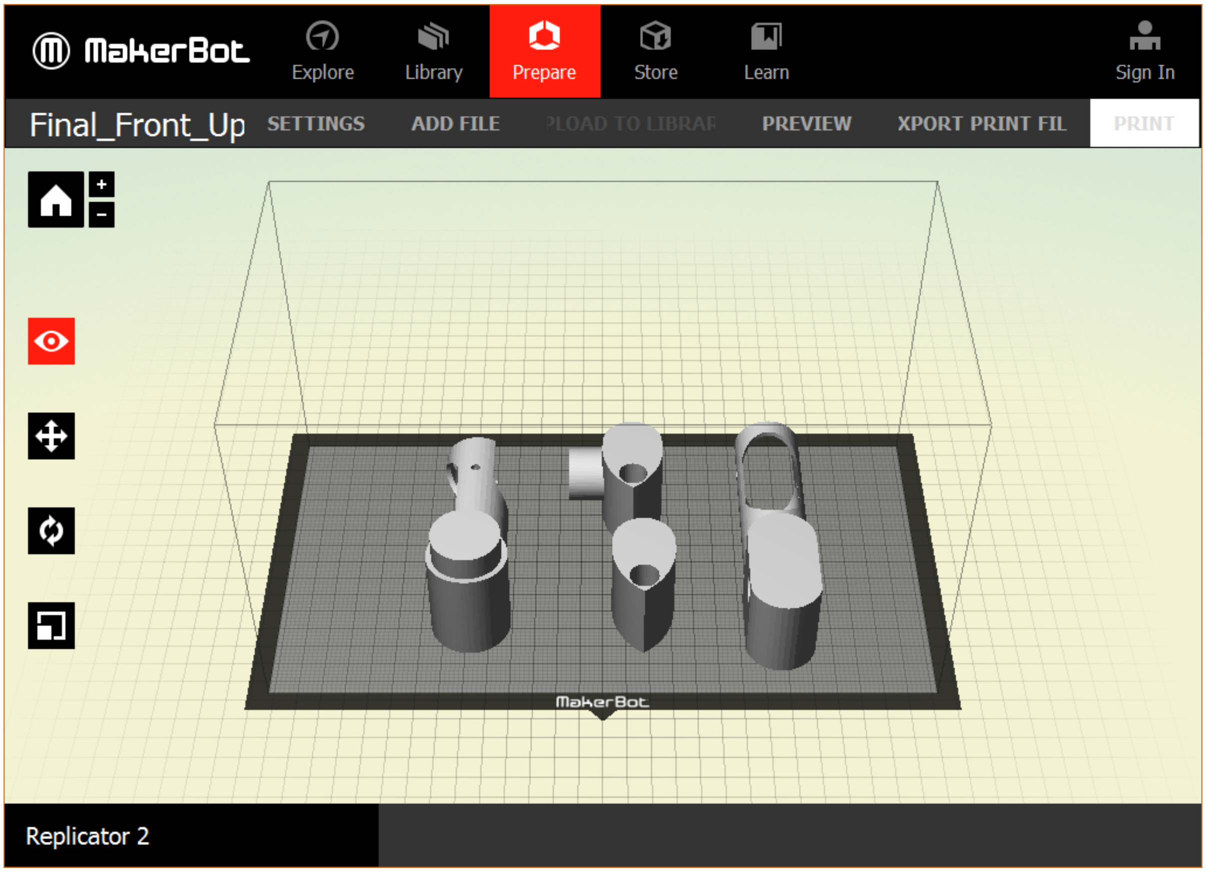


Figure 5.5: Screenshot of MakerBot software preparing to print four individual GaitScanner components.

After the initial print using the MakerBot Replicator 2 machine it was decided that four of the eight components did not print to a satisfactory standard. This could be attributed to multiple factors including the 1 mm tolerance, which was not accounted for in the 3D CAD model and the recent service history of the machine. Due to the intricacies of those parts it was decided that they would be reprinted using the Stratasys Connex 260 3D printer at the Flinders Innovation Centre. The Stratasys Connex 260 utilises a polyjet technology to create various models and prototypes with precision. It is a high quality, multi-material 3D printer that offers 14 customisable material selections including rigid and rubberised/flexible finishes that can be produced as an assembly, with up to 16-micron layer resolution (Flinders Innovation Centre, 2016). Figure 5.6 shows a comparison between the same 3D model printed using the MakerBot Replicator 2 (left) and the Stratasys Connex 260 (right). The high precision does come at a cost, with the filament price approximately $1000 AUD/kg, the full cost breakdown for GaitScanner is detailed in Section 5.1.4.

Figure 5.6: Comparison of 3D printing: MakerBot Replicator 2 (left) and Stratasys Connex 260 (right).

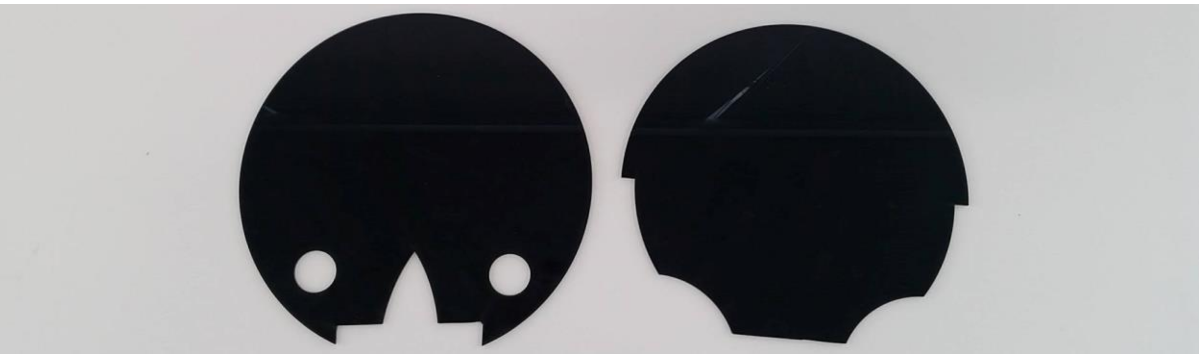


Figure 5.7: Laser cut acrylic in the shape of the end plates for the PVC pipe.

For larger components it can be more efficient to laser cut acrylic to the desired shape and size rather than 3D printing. A total of three components were laser cut, including two end covers for the PVC pipe, shown in Figure 5.7, and an internal mounting plate for the electronic components. All of the wiring was designed around the dimensions of the old prototype, thus many of the wires were extended and resoldered to the appropriate lengths such that it suited the new GaitScanner prototype. Once the wiring had been adjusted and the internal acrylic mounting plate was cut, the componentry was screwed into place, as represented in Figure 5.8

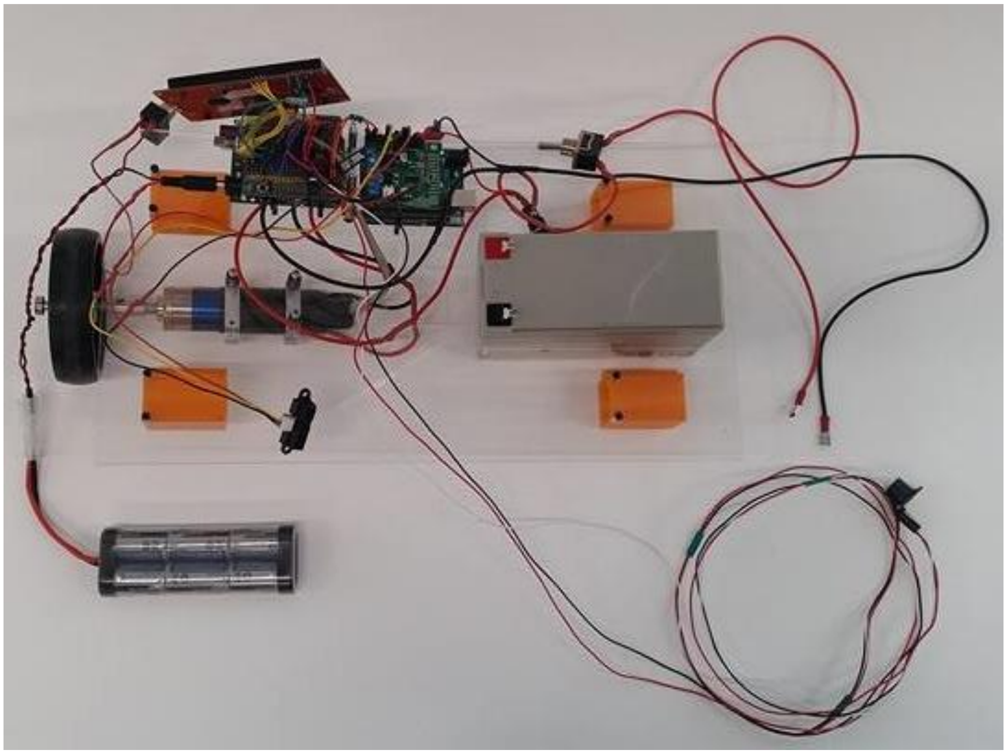


Figure 5.8: Acrylic mounting plate with electronic componentry in their respective locations.

5.1.3.4 Final Assembly

The final stage of prototype construction involved assembling all of the individual components into the final GaitScanner. Figure 5.9 shows all of the 3D printed wheel mounts with the wheels, bearings and drive shaft installed. Once the wheels had been installed, they were connected to the aluminium three and two tier extendable arms. The wheel mounts were then fixed to the side of the PVC pipe, as represented in Figure 5.10. The electronic components on the mounting plate was then inserted into the PVC pipe. Finally, the remainder of the components were put in their appropriate locations. Figure 5.11 shows the final assembly of the new GaitScanner prototype in both its extended (top image) and compacted (bottom image) form.

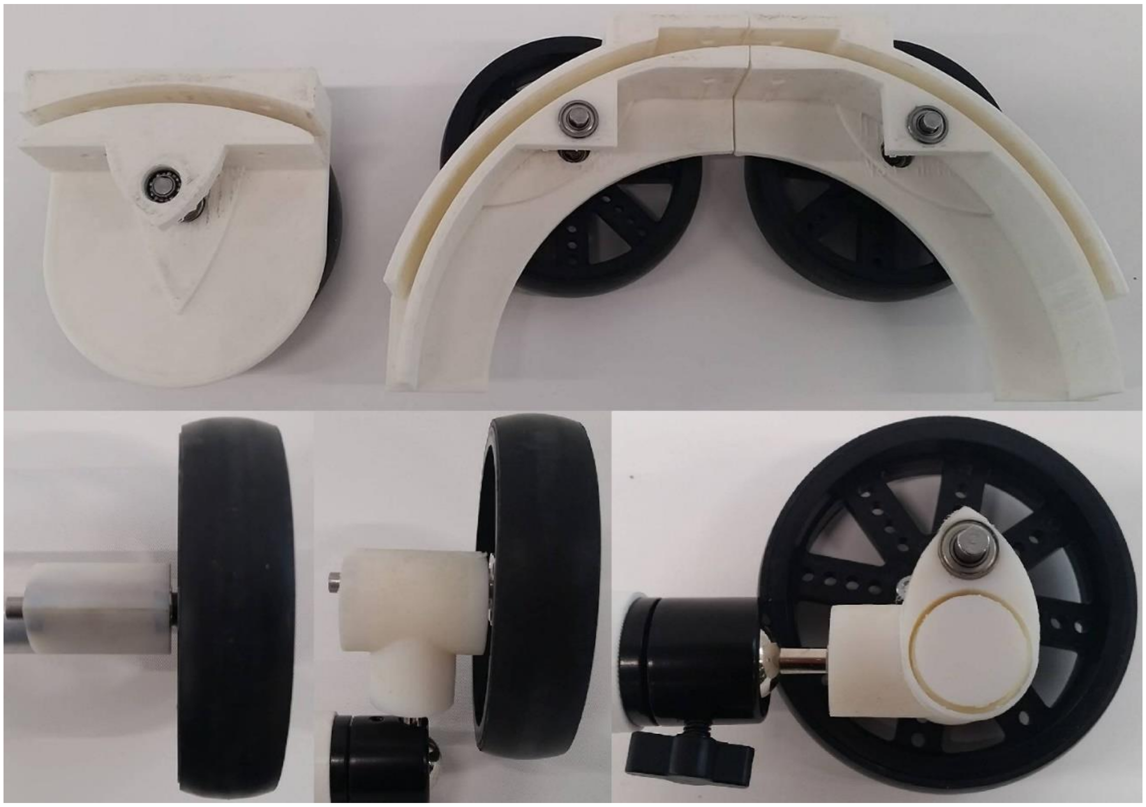


Figure 5.9: 3D printed wheel mounts with the wheels, bearings and the drive shaft installed.

Figure 5.10: 3D printed wheel mounts with the wheels connected to the edge of the pipe.

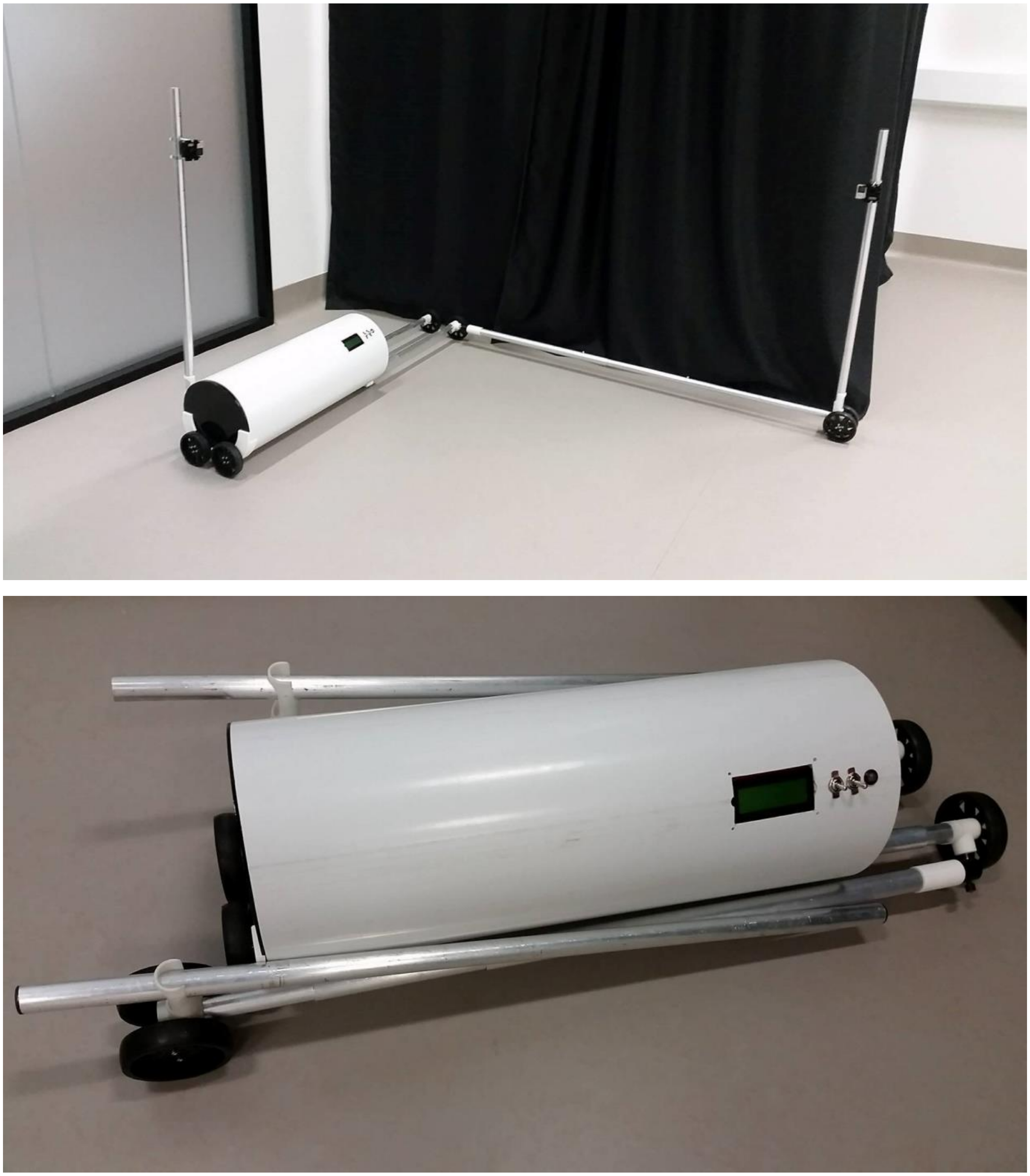


Figure 5.11: Final construction of the GaitScanner Prototype, extended size (top) compact size (bottom)

5.1.4 Cost Breakdown

The total cost of the new GaitScanner prototype is broken in Table 5.2. The table details whether the component is new or reused and its cost in Australian Dollars. The costs of each material were accurate at the time of purchase and do not include the costs of shipping and handling.

Table 5.2: Cost breakdown of all components used to contstruct the new GaitScanner prototype.

Component	New/Reused	Quantity	Cost/Unit $	Total Cost $
Arduino Uno R3	Reused	2	$45.95	$91.90
Motor Driver Shield	Reused	1	$75.46	$75.46
Motor (with gearhead and encoder combination)	Reused	1	$1100	$1100
Sharp IR Proximity Sensor	Reused	1	$15.95	$15.95
GoPro Camera Mount	Reused	2	$15.18	$30.36
GoPro Hero4 Silver Edition	Reused	2	$547	$1094
GoPro Smart Remote	New	1	$119	$119
SanDisk Ultra 32GB Micro SD	Reused	2	$29	$58
4” Heavy Duty Wheels	Reused	8	$6.99	$55.92
¼” Ball Bearing	Reused	16	$9.86	$157.76
2.25” D Shaft	Reused	8	$2.74	$21.92
7.2 V Battery	Reused	1	$11.76	$11.76
12 V Battery	Reused	1	$26.84	$26.84
Battery Charger	Reused	2	$59.95	$59.95
IR Remote	Reused	1	$8.95	$8.95
LCD Screen	Reused	1	$10.95	$10.95
LeddarOne Leddar Range Finder	New	1	$151.33	$151.33
PVC Pipe	New	1	$44.25	$44.25
1m 28.58 mm Aluminium Tube	New	3	$13.50	$40.50
2m 25 mm Aluminium Tube	New	1	$16.99	$16.99
1m 22.23 mm Aluminium Tube	New	1	$10.80	$10.80
Snap Button Single End	New	5	$2.68	$13.40
MakerBot Replicator 2 3D Print	New	1 kg	$37.95/ kg	$37.95
Stratasys Connex 260 3D Print	New	170 g	N/A	$380
Laser Cut Acrylic	New	2 Sheets	N/A	N/A
Wire/Nuts/Bolts/Screws	Resued	N/A	N/A	N/A
			TOTAL	**$3633.94**

5.2 Video Playback GUI

The Video Playback GUI was made using MATLAB R2015a Student License. The structure of the program can be broken down into a flow diagram, shown in Figure 5.13.

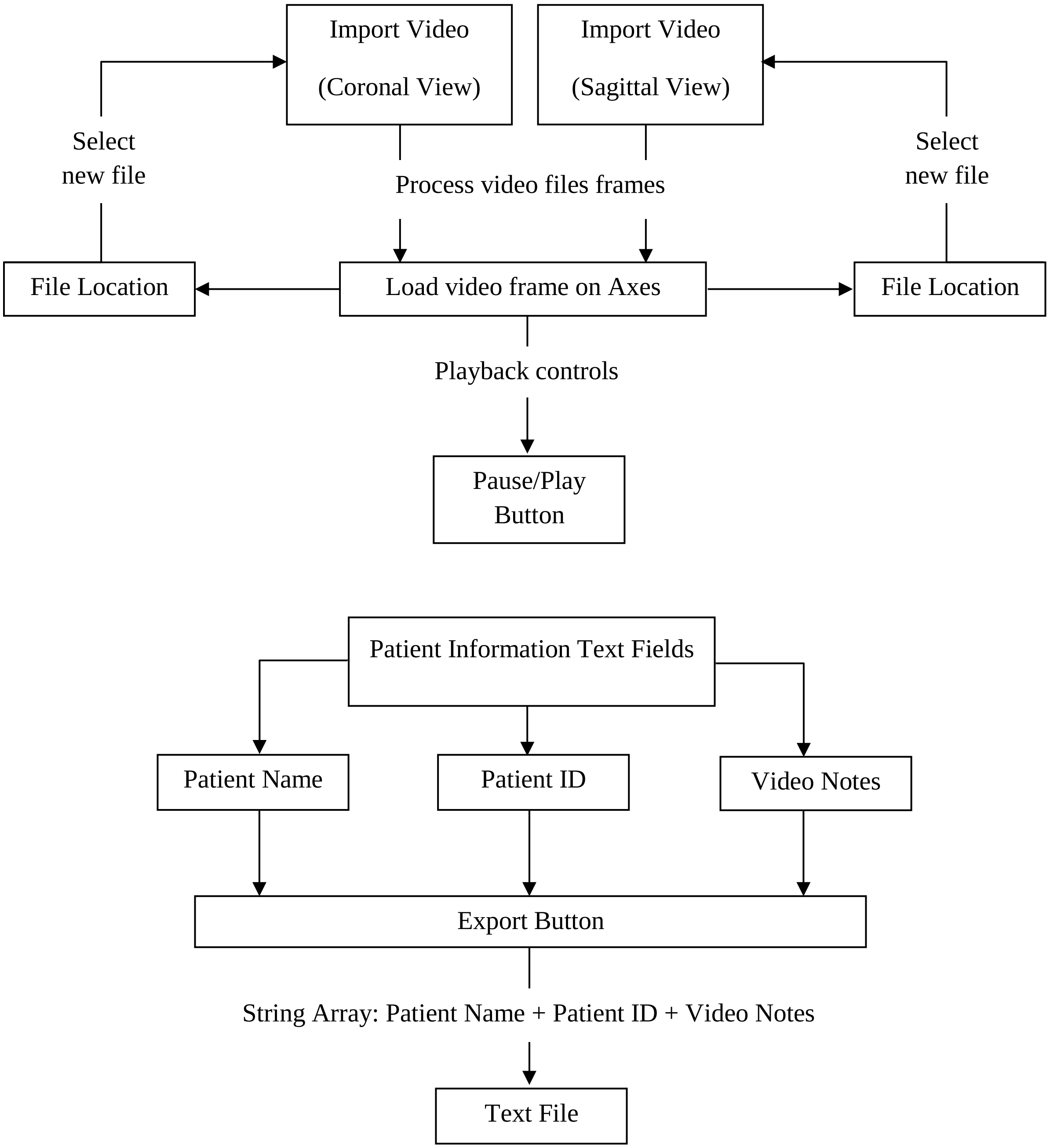


Figure 5.13: Function diagram of the process used to develop the MATLAB video playback GUI.

The program was developed using the Graphical User Interface toolbox on MATLAB. The toolbox has in built objects such as a textbox, text field, push button and axes etc. These features were selected and placed in the configuration shown in Figure 5.14.

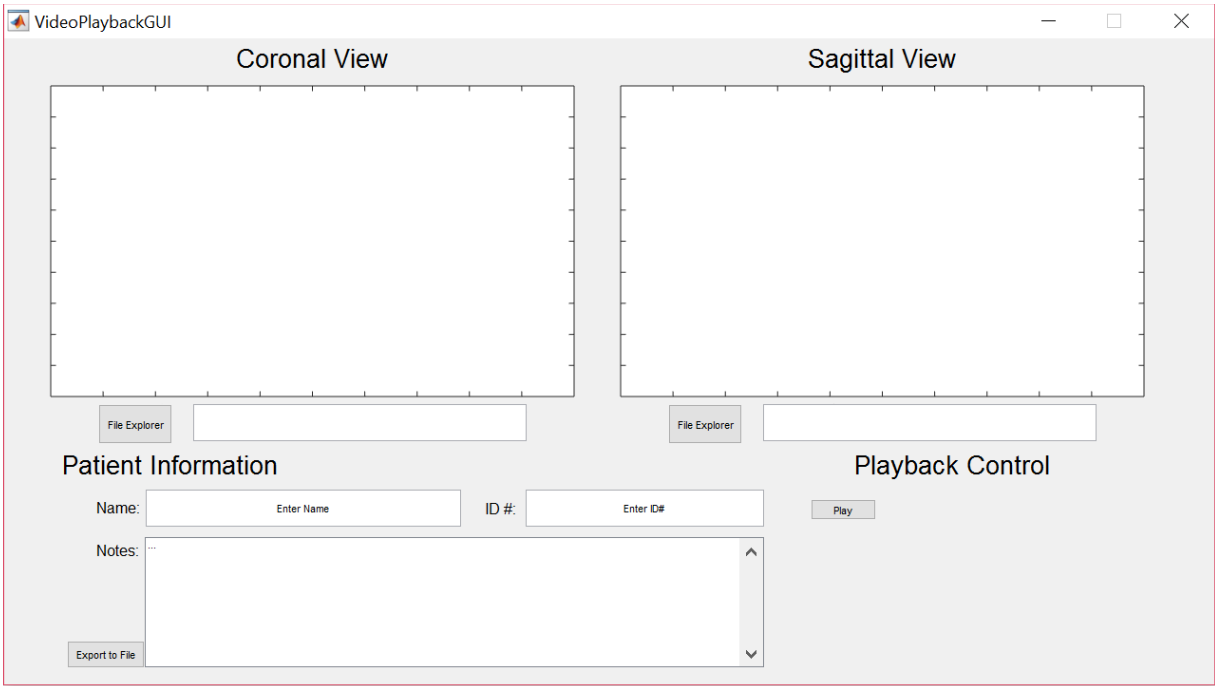
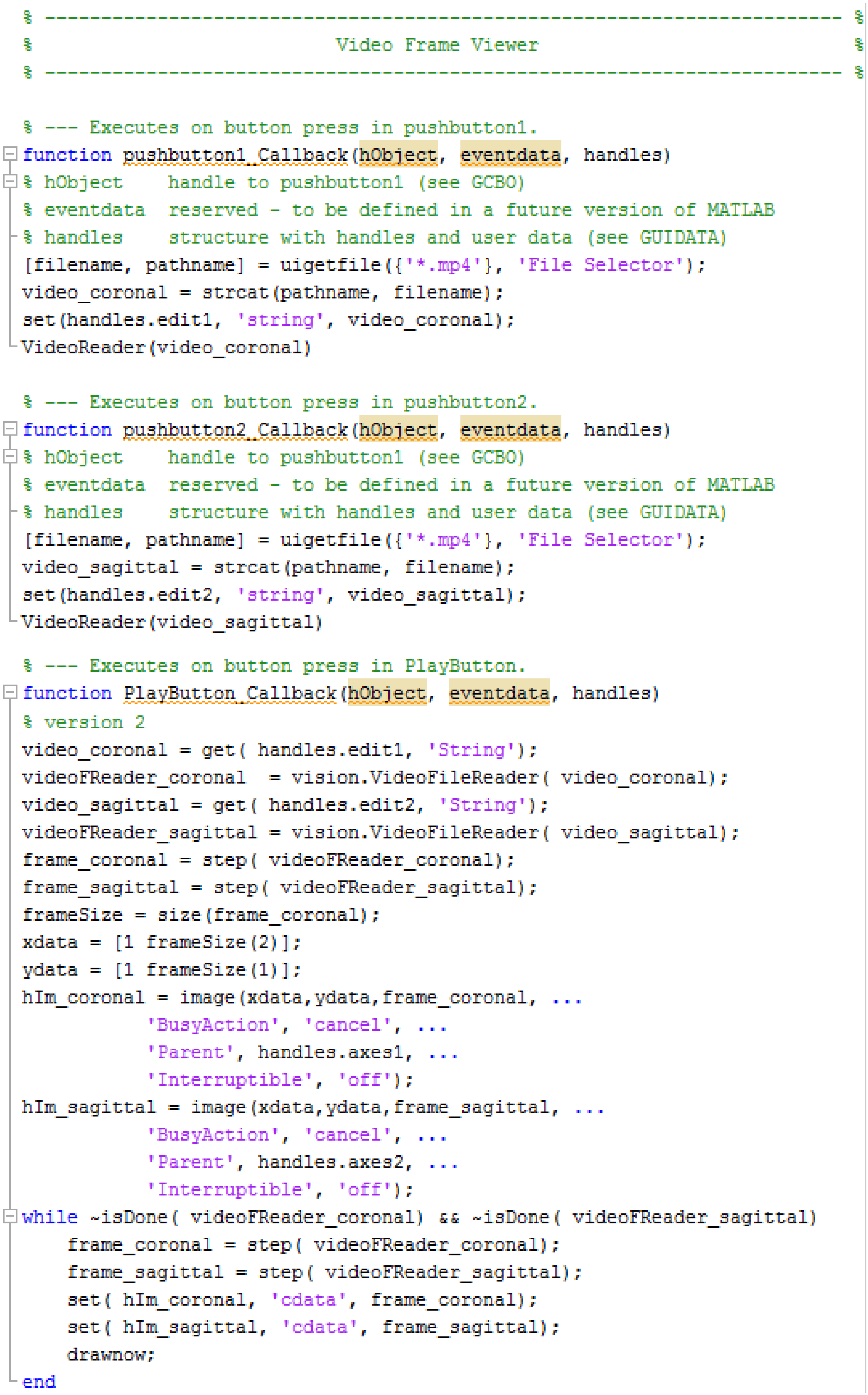


Figure 5.14: Using the MATLAB GUI maker toolbox to develop the Video Playback GUI.

The first action created is the importing of the video files using a pushbutton_Callback, the file is selected and the file path is saved as a string for access. The strings are then passed to display the frames on the axes. Once the play button is clicked the video will begin to play through frame by frame. The initial code can be seen in Figure 5.15. New videos can be constantly reloaded using the 'File Explorer' button. One issue encountered when both videos are played simultaneously is the that the framerate slowed to 20 fps.

The three text fields in the patient information section all allow for the clinician to input information. The three individual text fields save the inputs as three individual strings, the export button takes these strings and places them into string array before being exported as a txt file. The full code and associated files can be found in in Appendix D.



```
% ----------------------------------------------------------------------- %
%                           Video Frame Viewer                            %
% ----------------------------------------------------------------------- %

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
[filename, pathname] = uigetfile({'*.mp4'}, 'File Selector');
video_coronal = strcat(pathname, filename);
set(handles.edit1, 'string', video_coronal);
VideoReader(video_coronal)

% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
[filename, pathname] = uigetfile({'*.mp4'}, 'File Selector');
video_sagittal = strcat(pathname, filename);
set(handles.edit2, 'string', video_sagittal);
VideoReader(video_sagittal)

% --- Executes on button press in PlayButton.
function PlayButton_Callback(hObject, eventdata, handles)
% version 2
video_coronal = get( handles.edit1, 'String');
videoFReader_coronal  = vision.VideoFileReader( video_coronal);
video_sagittal = get( handles.edit2, 'String');
videoFReader_sagittal = vision.VideoFileReader( video_sagittal);
frame_coronal = step( videoFReader_coronal);
frame_sagittal = step( videoFReader_sagittal);
frameSize = size(frame_coronal);
xdata = [1 frameSize(2)];
ydata = [1 frameSize(1)];
hIm_coronal = image(xdata,ydata,frame_coronal, ...
           'BusyAction', 'cancel', ...
           'Parent', handles.axes1, ...
           'Interruptible', 'off');
hIm_sagittal = image(xdata,ydata,frame_sagittal, ...
           'BusyAction', 'cancel', ...
           'Parent', handles.axes2, ...
           'Interruptible', 'off');
while ~isDone( videoFReader_coronal) && ~isDone( videoFReader_sagittal)
    frame_coronal = step( videoFReader_coronal);
    frame_sagittal = step( videoFReader_sagittal);
    set( hIm_coronal, 'cdata', frame_coronal);
    set( hIm_sagittal, 'cdata', frame_sagittal);
    drawnow;
end
```

Figure 5.15: Initial code for the Video Playback GUI (pushbutton_Callback).

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6.

User Manual

This chapter will serve as a user manual for anybody who is using the GaitScanner for the first time or someone who may need a brief refresher on how to use the device or any of its complementary software. In addition to explaining how to operate the different modes of the GaitScanner, the user manual covers the basic setup and storage procedure, the setup of cameras such they can be controlled simultaneously using a single remote control, the comprehensive explanation of the video playback program GUI and a detailed list of safety precautions.

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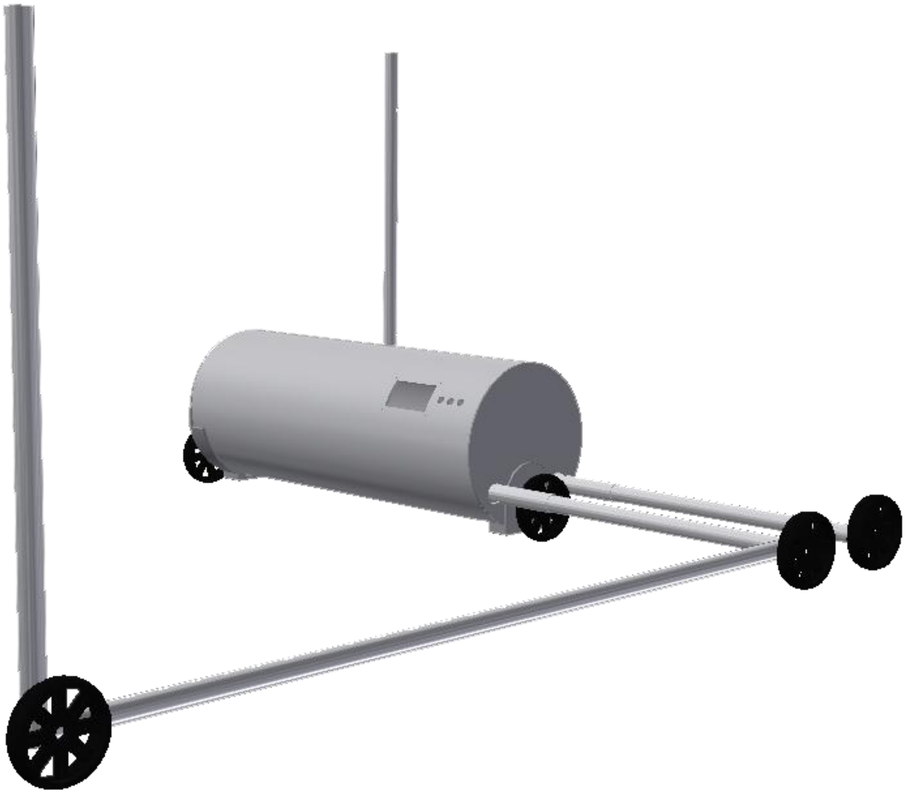
GaitScanner PVGL

Series 1. User Manual



Read these instructions carefully before using your GaitScanner, and keep it carefully.

If you follow the instructions, your GaitScanner will provide you with many years of good service.

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Welcome

GaitScanner
PVGL

Dear GaitScanner Owner,

Welcome to the world of GaitScanner. As an owner of the GaitScanner Portable Video Gait Laboratory Robot, you join a growing group of people around the world who, like you, are taking the steps to discover an easier way to record and analyse gait.

The use of the GaitScanner will help both in and outside of the clinical environment. Thank you for joining the GaitScanner movement. Your support and feedback is highly valued to the GaitScanner team. We look forward to your valued input as we continue to open new doors delivering revolutionary products that will lead change in the autonomous device space one step at a time.

On behalf of the entire GaitScanner team,

Daniel Thomas

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Table of Contents

Important Safety Instructions

TO REDUCE THE RISK OF FIRE, ELECTRIC SHOCK, OR INJURY

WARNING: TO REDUCE THE RISK OF FIRE OR ELECTRIC SHOCK DO NOT REMOVE PARTS INSIDE. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.

WARNING: TO REDUCE THE RISK OF FIRE OR ELECTRIC SHOCK, DO NOT EXPOSE THE APPLIANCE TO RAIN OR MOISTURE.

The lightning symbol within a triangle means “electrical caution!” It indicates the presence of information about operating voltage and potential risks of electrical shock.

The exclamation point within a triangle means “caution!” Please read the information next to all caution signs.

SERIAL NO: 0001

Notice: The GaitScanner contains a software interface for the purpose of enabling the manufacturer to provide updates to the internal firmware if any such updates are made available to the users. Any attempt to access, retrieve, copy, modify, distribute or otherwise use any of the GaitScanner software is strictly prohibited.

You should read these Important Safety Instructions. Keep these instructions in a safe place.

To avoid the risk of injury or damage, these basic precautions should always be adhered to:

- Read & keep these instructions.
- Heed all warnings & follow all instructions.
- Only use the GaitScanner in accordance with the specifications outlined in this manual
- Refer all servicing to qualified service personnel. Servicing is required when the GaitScanner has been damaged in any way, such as charger cord or battery plug is damaged, liquid has been spilled or objects have fallen into the GaitScanner, the GaitScanner has been exposed to rain or moisture, has been dropped or the enclosure is damaged, or does not operate normally or changes in performance in a significant way.

USE RESTRICTIONS

- The GaitScanner is not a toy.
- Do not use this apparatus near water.
- Clean only with dry cloth.
- The GaitScanner is for use on level hard surfaces only.
- Operate at room temperature. Do not operate or store directly near any freezing or extreme heat sources such as heaters, stoves, or other apparatus that produce extreme temperatures.
- The GaitScanner shall not be exposed to dripping or splashing and that no objects filled with liquids, such as vases, shall be placed on or around the GaitScanner.

BATTERY AND CHARGING

- Connect only to AC power outlets rated: 100/120V 220/240V 50/60Hz (depending on the voltage range of the included power supply).
- This GaitScanner shall be connected to a MAINS socket outlet with a protective earthing connection for charging.
- Protect the charger power cord from being walked on or pinched particularly at plugs, convenience receptacles, and the point where they exit from the battery.
- Only use attachments/accessories specified by the manufacturer.
- Unplug the battery during lightning storms or when apparatus is fully charged.

6.1 Overview

Welcome to the GaitScanner User Manual. This guide contains in-depth details of the GaitScanner's features and functionality. Please be sure to also read through your GoPro Hero 4 Silver Manual and GoPro Wi-Fi Remote Manual for detailed information on these peripherals.

The user manual is structured in the following layout.

1. Features Diagram

   The key features of the various components of the GaitScanner are identified in this Section of the User Manual.

2. Battery and Charging

   The details of the batteries and the correct charging methods are described in this section of the User Manual.

3. Before Operation

   Before the GaitScanner is ready for operation the setup and preparation is required. The necessary steps are detail in this section of the User Manual

4. Operation

   All of the necessary steps to operate the GaitScanner are detailed in this section of the User Manual.

5. Video Playback Software

   All of the necessary steps to operate the Video Playback program are detailed in this section of the User Manual

6. Troubleshooting

   Any possible issues regarding the operation of the GaitScanner or its relevant applications are discussed in this section of the User Manual.

6.2 Features Diagram

6.2.1 GaitScanner

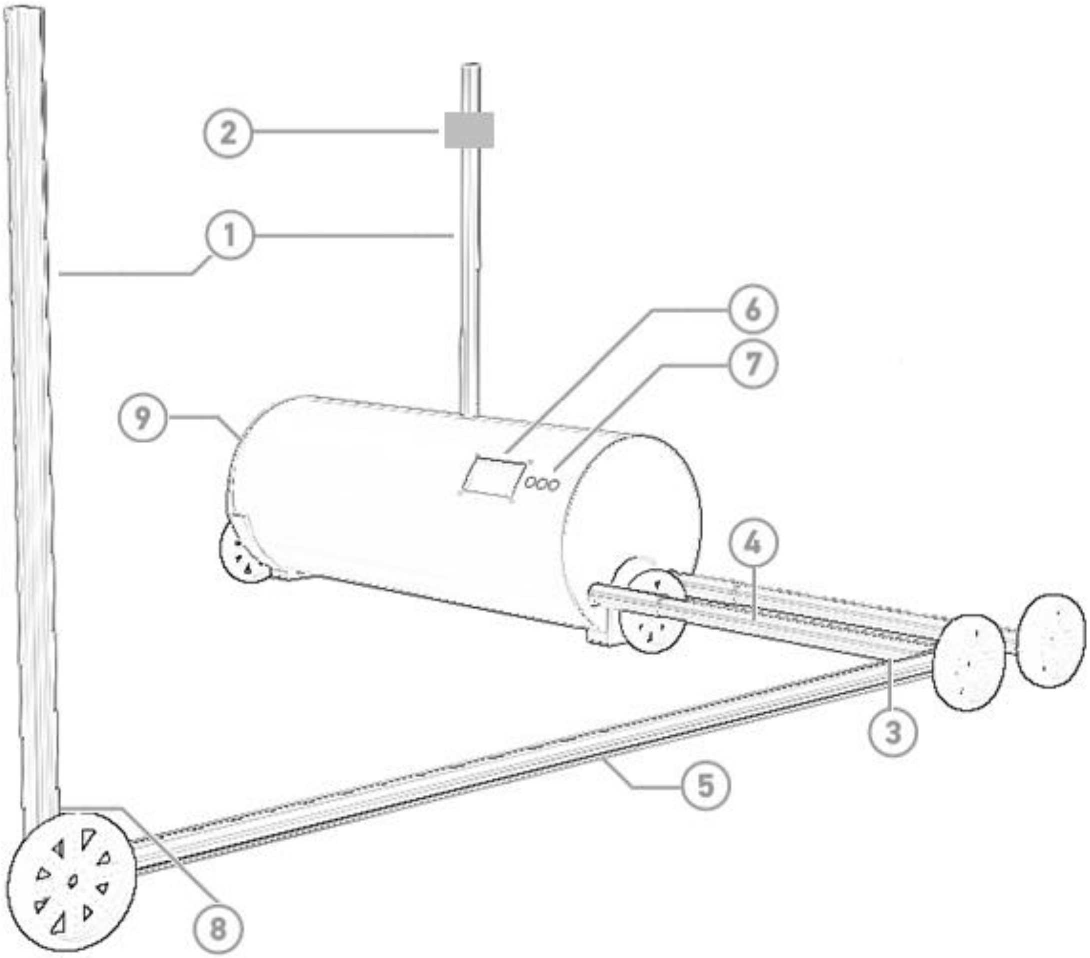


Figure 6.1: GaitScanner body features diagram

1. Upright Camera Mounting Pole
2. User Sensor
3. 90° Locking Hinge
4. 1-Stage Snap Lock Telescopic Pole
5. 2-Stage Snap Lock Telescopic Pole
6. LCD Screen
7. Power Switches
8. Collapsible Camera Pole Hinge
9. Removable Access Panel

Specifications

Model:	Prototype 4
Rated Voltage:	12 V, 7.2 V
Connectivity:	USB 2.0
Body Diameter:	⌀ 250mm
Minimum Dimensions:	~ mm x ~ mm x ~ mm
Maximum Dimensions:	~ mm x ~ mm x ~ mm
Net Weight:	Approx. ~ kg

6.2.2 IR Navigation Remote

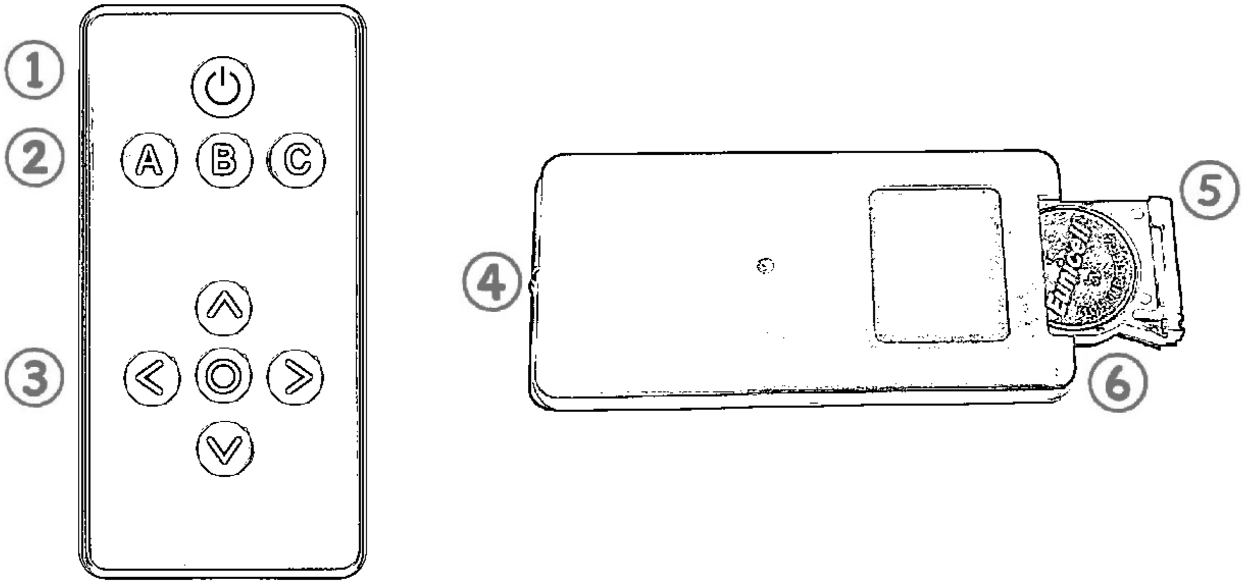


Figure 6.2: IR Navigation Remote features diagram

1. Power Button
2. Function Buttons
3. Control Buttons
4. IR Transmitter
5. Battery Cover
6. CR2025 3V Coin Cell Battery

6.2.3 GoPro Hero 4 Silver

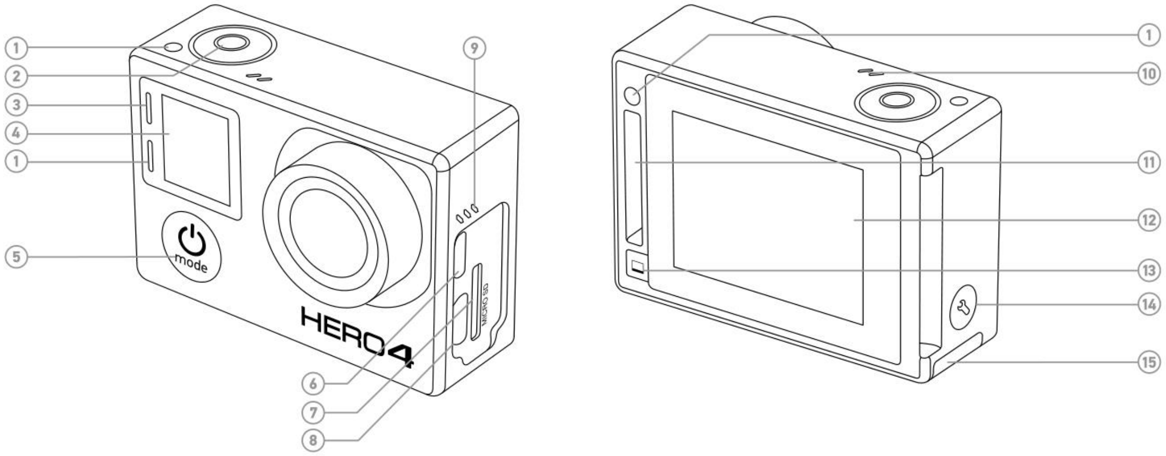


Figure 6.3: GoPro Hero 4 Silver features diagram

1. Camera Status Light (red)
2. Shutter/Select Button
3. Wireless Status Light (blue)
4. Camera Status Screen
5. Power/Mode Button
6. Micro HDMI Port
7. microSD Card Slot
8. Mini-USB Port
9. Audio Alert
10. Microphone
11. HERO Port
12. Touch Display
13. Touch Display Sleep/Wake Button
14. Settings/Tag Button
15. Battery Door

*Please refer to official GoPro Hero 4 Silver manual for further details regarding the operation of this device.

6.2.4 GoPro Wi-Fi Remote

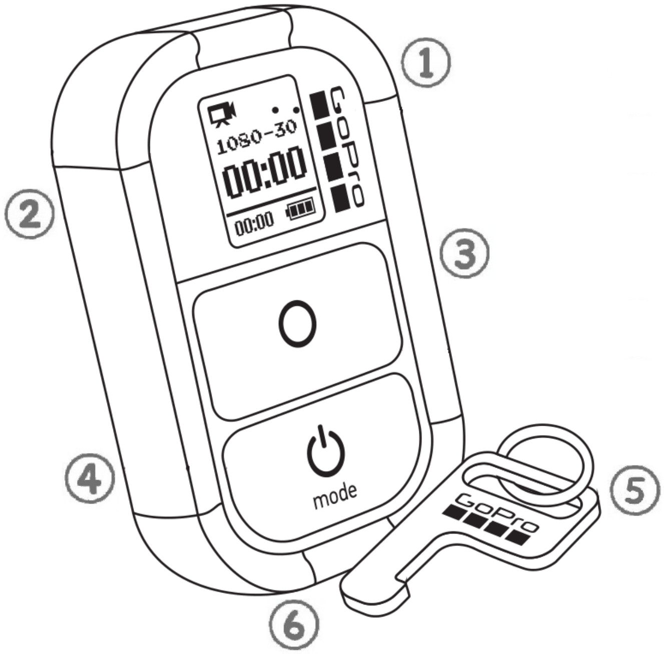


Figure 6.4: GoPro Wi-Fi Remote features diagram

1. LCD Display
2. Status LED
3. SHUTTER/SELECT Button
4. POWER/MODE Button
5. Removable Attachment Key & Key Ring
6. Charging Port/Attachment Key Slot

*Please refer to official GoPro Wi-Fi manual for further details regarding the operation of this device.

6.3 Battery and Charging

6.3.1 Battery Information

Table 6.1: Battery charge and discharge times

	12V Battery #1	7.2V Battery #2	GoPro Hero 4 Silver	GoPro Wi-Fi Remote
Run Time	~ 10 hours	~ 60 minutes	90 min at 1080p 60 fps, 105 min at 720p 120 fps	5-6 hours continuous use
Charge Time	~ 4 hours	~2 hours	2 hours via USB wall adapter, 4 hours via USB to computer	90 minutes

6.3.2 Charging Information

6.3.2.1 12V Battery #1

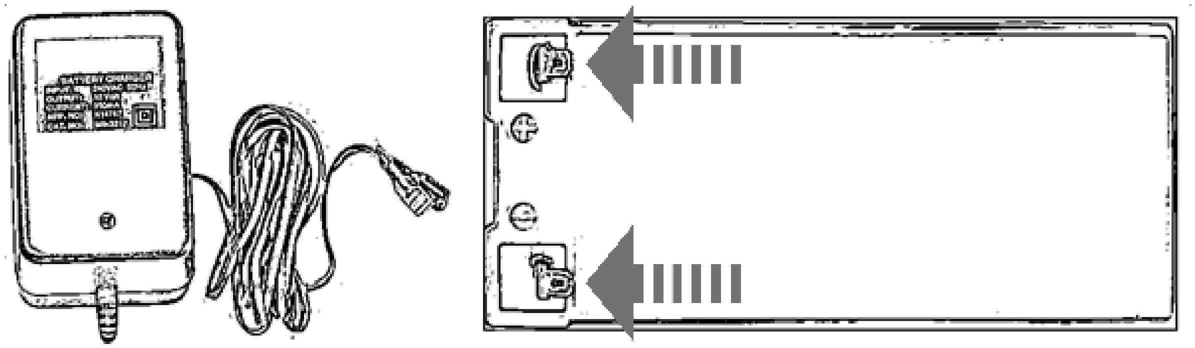


Figure 6.5: 12V battery charge diagram

Remove the left side panel of the GaitScanner and disconnect the 12V battery from the internal battery clips. Plug the adapter into a standard electrical outlet and into the battery’s clips. Charge the battery until the solid red light on the adapter turns off.

6.3.2.2 7.2V Battery #2

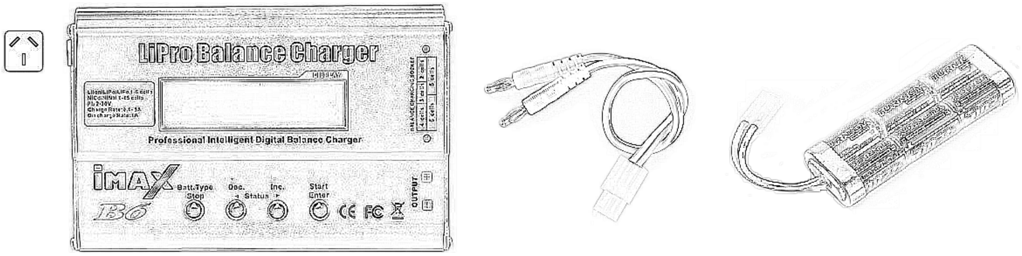


Figure 6.6: 7.2V battery charge diagram

Remove the left side panel of the GaitScanner and disconnect the 7.2V battery from the internal battery plug. Plug the LiPro Balance Charger into a standard electrical outlet. Plug the bullet charger leads into the output sockets and attach the battery via the Tamiya connector. Disconnect the battery

6.3.2.3 GoPro Hero 4 Silver

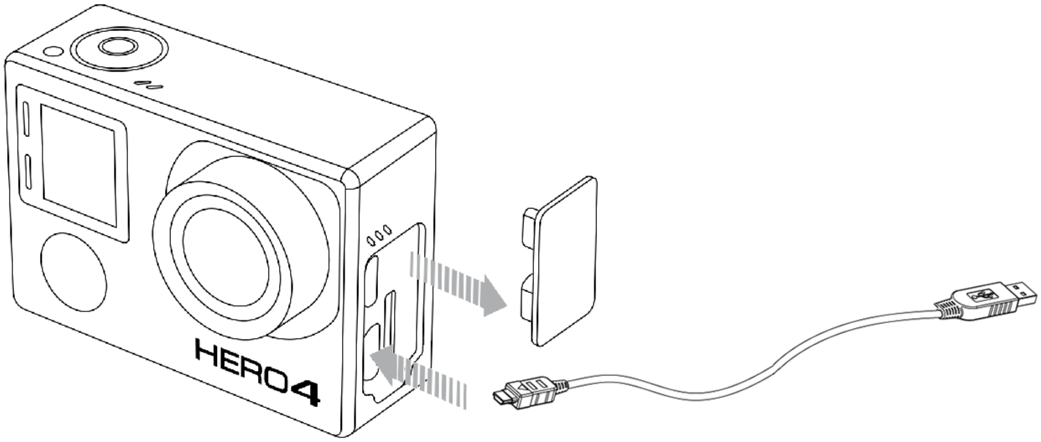


Figure 6.7: GoPro Hero 4 Silver charging diagram

Charge the battery by removing the camera side door and connecting the camera to a computer or other USB charging adapter using the included USB cable. The camera status light turns on during charging and turns off when charging is complete.

6.3.2.4 GoPro Wi-Fi Remote

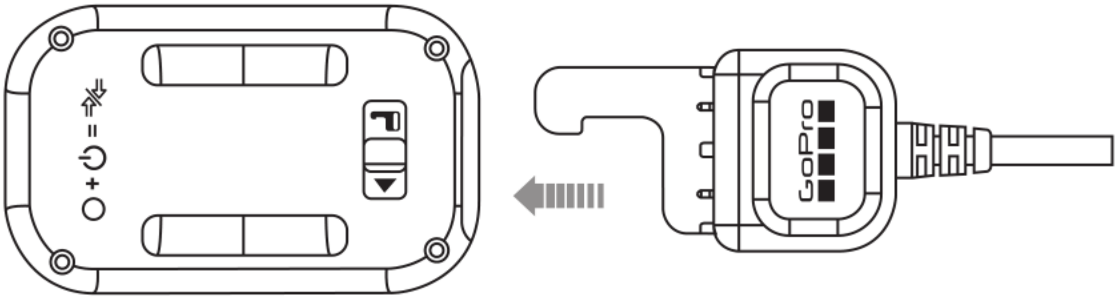


Figure 6.8: GoPro Wi-Fi Remote charging diagram

The LCD screen displays the Wi-Fi Remote's battery level while the Wi-Fi Remote is powering ON or charging. To charge plug charging cable into charging slot until it clicks. To remove charger slide and hold the latch lever in the direction of the arrow, then remove the charging cable.

6.4 Before Operation

6.4.1 Preparing the GaitScanner

Before the GaitScanner is ready for use it must be assembled following these five simple steps:

1. Prepare the primary front upright camera pole
2. Extend the primary wheel axels to full length
3. Disengage the twist lock and set the follower arm into position before reengaging the lock
4. Extend the follower arm to full length
5. Prepare the secondary upright camera pole

6.4.2 Pairing the GoPro Wi-Fi Remote

KEY:

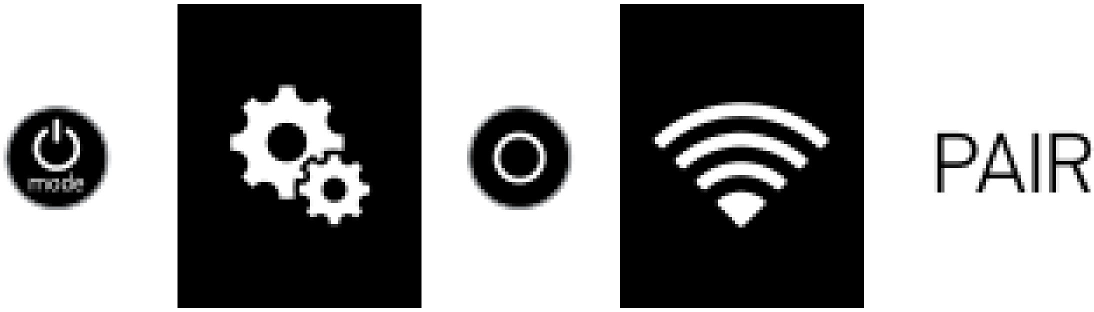


Figure 6.9: GoPro icons and menus

Enabling Camera Wi-Fi

1. Turn on camera by pressing the front Mode button.
2. Push the Mode button to cycle through to the Settings menu and select by pushing the top Shutter button.
3. Push the Mode button to cycle through to the Wireless Controls option and select by pushing the top Shutter button.
4. Select the Wi-Fi Icon.
5. Push the Mode button to highlight Wi-Fi RC option and select by pushing the top Shutter button.
6. Select New and the camera will begin looking for the Wi-Fi Remote.
7. Repeat steps 1-10 with all additional cameras.

Connecting the Wi-Fi Remote to the Cameras

1. Turn on the Wi-Fi Remote
2. Press and hold the Shutter button and press the Mode button.
3. Continue to hold down the Shutter button until all cameras a connected (a check mark will appear on the camera's LCD screen).
4. Once the remote's LCD screen displays the appropriate number of connected cameras, push the Mode button on the remote to finalise the pairing process.
5. The Wi-Fi Remote will then be ready for use.

6.5 Operation

6.5.1 Turning on the device

Turn of both switches located at the front on the device such that the light turns on displaying a bright green colour. Once the switches have been turned on take the *IR Navigation* remote control and press the *Power Button* to turn on the LCD Screen ready for operation.

6.5.2 The Home Screen/Selecting a Mode

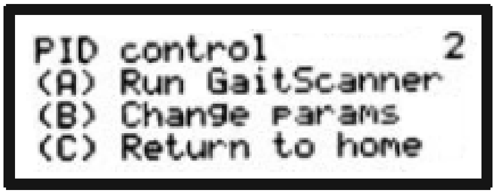
```
GaitSCANNER       1

(A) PID ctrl
(B) Const Spd ctrl
```

Figure 6.10: Home Screen/Mode Select Screen

Once the GaitScanner has been turned on it will display the Home Screen. The Home Screen is where the primary mode of the GaitScanner is selected, the two options include PID Control and Constant Speed Control, shown in Figure 6.10.

The PID Control mode of the GaitScanner takes input information from the *User Sensor* to autonomously adjust the operating speed proportional to that of the user. The Constant Speed Control mode of the GaitScanner operates at a constant predefined speed regardless of the users speed.

6.5.3 Mode #1: PID Control

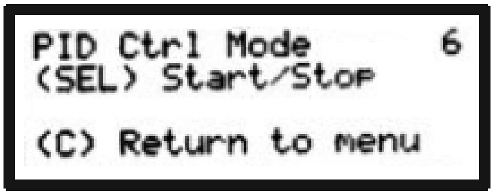


```
PID control        2
(A) Run GaitScanner
(B) Change params
(C) Return to home
```

Figure 6.11: PID Control Mode main screen

The PID Control Mode main screen has three options, shown in Figure 6.11:

a) Run GaitScanner, which takes the user to the start mode screen when selected
b) Change parameters, which takes the user to the PID Parameter screen when selected
c) Return to home, which takes the user back to the Home Screen when selected



```
PID Ctrl Mode      6
(SEL) Start/Stop

(C) Return to menu
```

Figure 6.12: PID Control starting screen

The start mode screen has two options, shown in Figure 6.12:

- (SEL) Start the GaitScanner, which starts the GaitScanner (Press (SEL) again to stop the GaitScanner)
- (C) Return to menu, which takes the user to the PID Control Mode main screen when selected

```
PID Params          4
(A) Kp: 2.50
(B) Ki: 0.00
(C) Kd: 0.00
```

```
PID Params          4
(^/v) Kp: 2.50
(B) Ki: 0.00
(C) Kd: 0.00
```

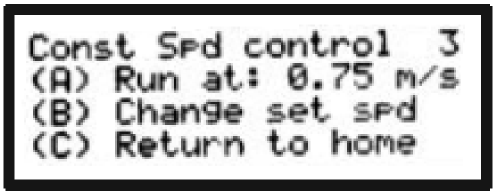
```
PID Params          4
(A) Kp: 2.60
(^/v) Ki: 0.00
(C) Kd: 0.00
```

```
PID Params          4
(A) Kp: 2.60
(B) Ki: 0.00
(^/v) Kd: 0.50
```

Figure 6.13: Menu for altering PID parameters

The PID Parameter screen allows the user to change the parameters of K_p, K_i and K_d. Each parameter can be changed by 1st pressing a selection button (A/B/C) followed by the UP/DOWN arrow keys, shown in Figure 6.13.

6.5.4 Mode 2: Constant Speed Control



```
Const Spd control   3
(A) Run at: 0.75 m/s
(B) Change set spd
(C) Return to home
```

Figure 6.14: Constant Speed Control Mode main screen

The Constant Speed Control Mode main screen has three options, shown in Figure 6.14:

a) Run GaitScanner at predefined speed, which takes the user to the start mode screen when selected
b) Change set speed, which takes the user to the Speed Parameter screen when selected
c) Return to home, which takes the user back to the Home Screen when selected

```
Constant Spd Mode   7
(SEL) Start/Stop
(^) Dir: Forward
(C) Return to menu
```

```
Constant Spd Mode   7
(SEL) Start/Stop
(^) Dir: Reverse
(C) Return to menu
```

Figure 6.15: Constant Speed Control starting screen

The start mode screen has three options, shown in Figure 6.15:

- (SEL) Start the GaitScanner, which starts the GaitScanner (Press (SEL) again to stop the GaitScanner)
- (^) Direction, which will change the travel direction of the GaitScanner from default forward to reverse
- (C) Return to menu, which takes the user to the PID Control Mode main screen when selected

```
Const Spd Param     5
(^/v) Spd: 0.75 m/s
(SEL) Confirm
```

Figure 6.16: Menu for altering Speed parameter

The Speed Parameter screen allows the user to change the speed parameter of the GaitScanner. The Speed parameter can be changed by pressing the UP/DOWN arrow keys, shown in Figure 6.16.

NOTE: The Speed can be adjusted from 0 m/s to 1.5 m/s.

6.5.5 Information Mode:

```
Proximity: 300 cm  8
Speed: inf m/s

(SEL) STOP MOTOR
```

Figure 6.17: Information Mode Screen

When the GaitScanner is in operation the screen will display the Information Mode screen. The screen will display the Proximity and the Speed, shown in Figure 6.17.

6.5.6 Updating the Firmware

The GaitScanner has been created to support future updates to the software. In order to update the firmware, connect the GaitScanner to a computer via the USB cable and copy the update file to the GaitScanner.

6.6 Video Playback Software

6.6.1 Connecting to a Computer

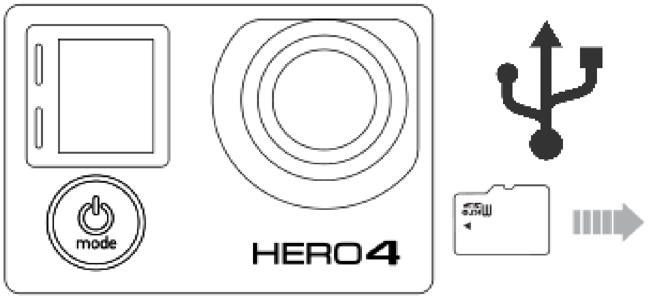


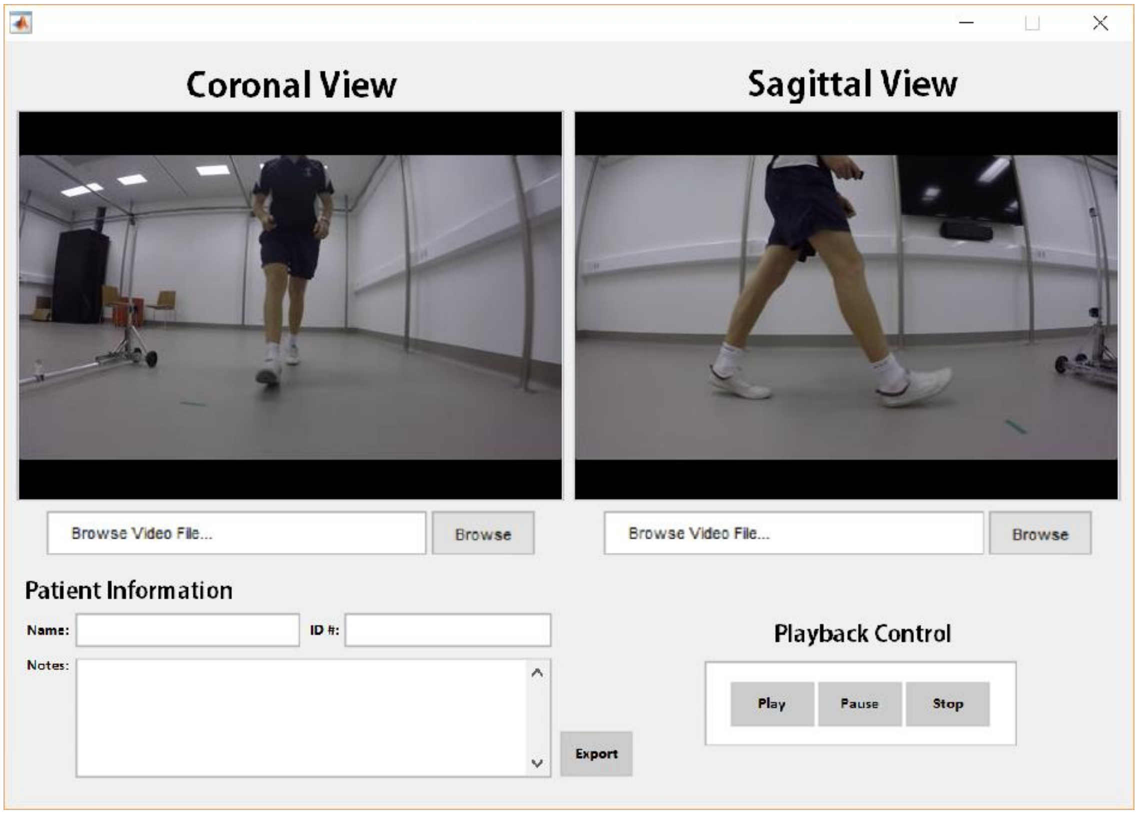
Figure 6.18: Connecting GoPro to computer via USB or microSD

The footage can be extracted from the GoPro camera using one of two methods:

1. Via direct USB connection
2. Via microSD card

It is recommended for best results that the files are first copied to the computer before accessing the files using the Video Playback program.

6.6.2 GUI Overview



Minimum System Requirements

	Windows	Mac
Operating System	Windows 7, 8.x, 10	OS X 10.8 or later
CPU	Intel ® Core 2 Duo ™ (Intel Quad Core ™ i7 or better recommended)	Intel ® Dual Core ™ (Intel Quad Core i7 or better recommended)
Graphics Card	Card that supports OpenGL1.2 or later	Card that supports OpenGL1.2 or later
Screen Resolution	1280 x 800 minimum	1280 x 768 minimum
RAM	4GB minimum	4GB minimum
Hard Drive	5400 RPM internal drive (7200 RPM drive or SSD recommended). If external, use USB 3.0 or eSATA	5400 RPM internal drive (7200 RPM drive or SSD recommended). If external, use Thunderbolt, FireWire or USB 3.0

6.6.3 Playing a Video

Load a video file by clicking on the browse button below the video box. Navigate to the desired video file and select ‘Load’ within the file explorer. Repeat this process for both coronal and sagittal view video files. Once both videos have been loaded, they can be simultaneously controlled using the universal playback control buttons located in the bottom right quadrant of the GUI window.

6.6.4 Patient Information

Patient information including name, identification number and video notes can be entered into the text fields located in the bottom right quadrant of the GUI window. Once all patient information has been entered the export button will allow the user to export the information to a text file, which can then be accessed again at a later date.

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7.

Discussion and Evaluation

7.1 Evaluation Against Requirements

To evaluate the overall success of the GaitScanner project, the outcomes can be evaluated against the initial project requirements developed with the client, shown in Section 3.1. This section details the authors analysis of how each individual requirement performed compared to the originally intended outcome. Each requirement was evaluated based on the overall performance during the tests conducted. A summary of the requirements evaluation is shown in Table 7.1, where each requirement was given a grade ranking to better quantify its individual performance and as a component of an entire system.

Table 7.1: A summary of the project requirements accompanied with the evaluation of performance grade

No. #	Requirement	Evaluation of Performance
1	Must capture subject gait from both the coronal and sagittal planes	A
2	Must not impede patient gait	A
3	Must be durable	B
4	Must be easy to operate	A
5	Must be of low cost	B
6	Must accommodate all users	A
7	Must be portable	A
8	Must have multi-surface capability	C
9	Must easily integrate with wearable 3rd party systems	C
10	Must reduce input lag upon acceleration/deceleration	C
11	Must have an enclosure for electronic components	A
12	Must record basic spatiotemporal data	C
13	Must have a simple means of video playback	A

7.1.1 Requirement #1 Evaluation

Must capture subject gait from both the coronal and sagittal planes

Evaluation grade: A

Adequate capture of uniform two-dimensional video capture of a subject’s lower body in the coronal and sagittal planes was paramount to the overall viability of the GaitScanner as a video analysis device. The GaitScanner allows for the high definition cameras to be mounted at any position along the upright poles. The ability to adjustability ensures that the subject’s lower body can always be centralised in the video frame regardless of their height.

Although a variety of commercial camera options were available, the GoPro Hero 4 Silver was chosen as the best camera in terms of picture quality, cost, size and ease of implementation. An addition to the camera system was a simple, cost effective remote control for synchronous control of both cameras. Video synchronisation is vital feature when analysing the subject gait data as all key gait events will be time correlated for easier identification and analysis during post processing, refer to Section 7.2.13 Requirement 13 Evaluation.

7.1.2 Requirement #2 Evaluation

Must not impede patient gait

Evaluation grade: A

During all of the elementary tests in evaluation the GaitScanner did not appear to impede the subject gait. The primary function of the GaitScanner is to capture natural gait and in all of tests the GaitScanner was still able to function as intended under these conditions without interfering subject gait. The updated enclosure design has minimised visual distractions by concealing the electronic componentry, refer to Section 7.2.11 for further details on the enclosure.

7.1.3 Requirement #3 Evaluation

Must be durable

Evaluation grade: B

The GaitScanner is a device that is intended to be used in clinical trials with over 100 subjects. As such the device needed an enclosure to protect the electronic componentry, but the structure as a whole must be durable enough to withstand general use. The ultimate test will its real world durability over time, which can only be tested with further use of the device.

7.1.4 Requirement #4 Evaluation

Must be easy to operate

Evaluation grade: A

All of the evaluation tests were undertaken solely by an individual. A remote is used to navigate through the various context menus of the GaitScanner and both of the cameras are triggered simultaneously to ensure synchronous video recordings. The video playback program interface was designed to be non-complex and accessible to all kinds of users, especially to people without a technical background. The effectiveness of the simple step-by-step user manual that also helps address any possible queries regarding the GaitScanner operation or setup was tested by a group of varying ages and mixed genders, to positive results.

7.1.5 Requirement #5 Evaluation

Must be of low cost

Evaluation grade: B

One primary drawback of current gait analysis technology is the high cost, as such making the GaitScanner an affordable device in comparison was paramount to the success of this project. Although the entirety of the project funds was spent on the construction of the prototype, the final cost of the GaitScanner was $3633.94, which is only a fraction of the cost of current gait analysis systems. A complete cost analysis breakdown of the purchased materials can be found in Section 5.1.4.

7.1.6 Requirement #6 Evaluation

Must accommodate all users

Evaluation grade: A

Since all subjects will not have the same condition, the major challenge was to ensure the device is able to accommodate all users. For the design of the prototype, the following parameters were considered: height, width, age, gender and gait ability. The adjustability of camera mounting positions accounted for any variances in height between different subjects and the 1.5 m/s speed range was suitable for those with different gait ability. Although width does not vary as much compared to height, many subjects require the assistance of walking aids, these aids can range from prosthetics, orthotics, through to a variety of walk assist frames. Thus, a test using a walking aid was performed and no difference in the GaitScanner’s performance was recorded.

7.1.7 Requirement #7 Evaluation

Must be portable

Evaluation grade: A

A major advantage of the GaitScanner over conventional gait analysis methods is its portability, such that the device can be used at locations other than laboratories located in specialised hospitals and rehabilitation centres. The device will provide comprehensive video gait analysis to a wider user base who may reside in residential care homes, hospitals, clinics and even to the people still living at home. The new design of the GaitScanner was a major improvement over the previous iterations, it saw an overall size reduction greater than 30% and weighs less than 10 kg. The reduced size makes it much easy to transport in the back of a car and store when not in use, the portability does not affect the function of the GaitScanner as it maintains the existing operating dimensions.

7.1.8 Requirement #8 Evaluation

Must have multi-surface capability

Evaluation grade: C

The GaitScanner was tested on both carpet and concrete surfaces, without experiencing any major issues. In one test trial however, the extendable guiding arm did not have complete surface contact causing the GaitScanner to deviate trajectory by a few degrees. Although the GaitScanner was unable to be tested on outdoor surfaces, it is envisaged that the GaitScanner will perform adequately on any even hard floor surface. The other important factor was the stability when moving over a flooring surface. Stability of the cameras are essential for clinician to make an accurate analysis of a patients' gait and after assessing the recorded video footage from the mock evaluation trials, the GaitScanner has exceeded initial expectations.

7.1.9 Requirement #9 Evaluation

Must easily integrate with wearable 3rd party systems

Evaluation grade: C

The GaitScanner was designed to be a complete system not reliant on external equipment or technology however, the ability to be compatible with 3rd party systems were an of interest to the client. The benefits of utilising other technology will allow for the analysis of additional gait characteristics such as spatiotemporal data, which would otherwise be unobtainable with the GaitScanner alone. Unfortunately, due to time constraints the GaitScanner could not be tested with any wearable footwear systems. It was however, tested with a VICON 3D kinematic measurement system at the motion analysis lab on Flinders University. The GaitScanner did not appear to interfere with the reflective marker technology or IR cameras, nor did the VICON system have an effect on the operation of the GaitScanner. The possibilities to integrate the GaitScanner with an advanced motion analysis system could something to research in the future.

7.1.10 Requirement #10 Evaluation

Must reduce input lag upon acceleration/deceleration

Evaluation grade: C

The previous iteration of the GaitScanner device is able to autonomously track human locomotion directly forwards and backwards however, there existed an input time delay upon acceleration and deceleration. This delay was responsible for both an overshoot and undershoot when the subject respectively increases or decreases their walking speed. In the evaluation testing, the revised control system was not able to be tested extensively in terms of accuracy, repeatability and delay measured in seconds. This has been addressed in Section 8.1.1 Project Finalisation. The new LeddarOne range finder, however, is a major improvement over the previous ultrasonic range finder and will undergo further testing to validate these claims.

7.1.11 Requirement #11 Evaluation

Must have an enclosure for electronic components

Evaluation grade: A

The enclosure for the GaitScanner was a major part of this project, as the client has expressed his desire to use the device for clinical trials, it was necessary to ensure the device would comply to basic safety regulations. The initial premise for the enclosure was create a cover for the exposed wires and electronic componentry however, after an extended design process it evolved into a complete redesign of the GaitScanner as a whole. The new GaitScanner prototype not only succeeds as enclosure that protects the internal components and increases the overall collapsibility, it also better aesthetically resembles a medical device that creates a more welcoming experience for the test subjects.

7.1.12 Requirement #12 Evaluation

Must record basic spatiotemporal data

Evaluation grade: C

It was previously identified that the PVGL has the potential to record basic spatiotemporal data, in the form of subject speed and total distance travelled. This would provide information to the clinician in addition to the data obtained from the video footage. This data would help greatly during the monitoring and diagnosis of subject conditions. In order to extract this data, the control system must be programmed to store the information in a logical manner that can be accessed at a later date for further analysis.

7.1.13 Requirement #13 Evaluation

Must have a simple means of video playback

Evaluation grade: A

Prior to the development the video playback program, the GaitScanner did not have a dedicated means of reviewing the recorded footage. Now any user is able to analyse the recorded video footage with both coronal and sagittal plane views displayed side-by-side in a user friendly interface. By incorporating simultaneous playback buttons to control both videos it provides a simpler way to diagnose and monitor a subjects’ condition. The program also has text fields where a clinician can enter any relevant information regarding the subject, which can then be exported and saved for access at a later date.

8.

Conclusion

While this thesis report must come to a close there are still areas of the project that need to be addressed to ensure the successful completion of the new and improved GaitScanner device. In addition to the remaining work required to be completed by the author, future recommendations to further improve the GaitScanner as a viable commercial alternative to conventional gait analysis techniques must be made. This chapter will address all these issues and topics, specifically discussing the immediate work that must be completed, suggesting possible ideas that could be explored in the coming years, before concluding with a closing statement from the author.

8.1 Post Thesis Work

8.1.1 Project Finalisation

In its current state the GaitScanner is able function completely as intended, providing a means of non-contact video gait analysis with enhanced portability when not in operation. However, one key client requirement that the GaitScanner does not satisfy is with regards to the aesthetics of the device; particularly the unfinished PVC pipe and raw aluminium pipe. It was previously identified that during gait analysis, distractions such as reflections or obvious equipment etc. can cause subjects to subconsciously alter their gait patterns. Due to this phenomenon, a requirement was put in place to ensure that the new GaitScanner prototype would cover any electronic or moving componentry and best resemble a medical device. In order so rectify this issue the exterior of the PVC and aluminium pipes must be painted. The PVC will be painted in a light beige colour, a soft tone often used for medical devices and the aluminium pipes will be painted in black to provide a small contrast to the beige enclosure. The GaitScanner will also need to have handles or grips for easier transportation to ensure a clinician is aware of which areas of the GaitScanner is suitable to be held without damaging the device.

The Video Playback program currently processes the coronal and sagittal videos on individual axes. A test program that processes and concatenates the two videos into a single file was created, the full MATLAB code can be found in Appendix. By slightly increasing the initial import/video processing time it was found that the concatenated video would playback at a higher framerate compared two individual videos. Thus, to improve the Video Playback GUI this process will be implemented during post thesis work. Additionally, a mark key event/frame button will be incorporated. This feature will allow a clinician to mark an event at a particular frame by a press of a button, saving the frame as an image file with the timestamp as the file name.

In order to rectify and reduce the input lag upon acceleration/deceleration of the device the control system requires the most attention during the final weeks of the project. Although the Arduino code for the Leddar Range Finder sensor was implemented to the control system the sensor was not functional its current state. Further testing of the control system detailed in Figure 4.17 must be conducted in the form of a mock clinical evaluation.

8.1.2 The Hand Over

Once the project has been finalised the primary objective will be to hand over ownership back to the project client, whereby the client is then able to decide the future of the GaitScanner project. During this handover process a brief demo will conducted to ensure the client is aware of the basic GaitScanner operating procedure of all its relevant functions, including the drive system controls, video capture and the post processing tools. Once this process is complete the client can begin the new phase of the GaitScanner project. Whether or not that involves discussing potential commercialisation opportunities to enter the marketplace, utilise the GaitScanner in at personal practise to reap the benefits firsthand while running tests on the device or quite possibly the GaitScanner could undergo further development to improve the prototype before begin the push to enter the marketplace.

After working on this project for some time, it has become evident that devices such as the GaitScanner is not commonly investigated and has limited source material in various academia including modern literature or patents. As such, the possibility to write and submit a paper concerning the GaitScanner as a novel alternative to conventional gait assessment is a major goal for those currently and previously involved throughout the entirety of this project.

8.2 Future Development

The following section details areas of the project that could benefit from some improvements. While possible solutions are proposed, it would be best to further investigate these issues before attempting to resolve or implement the suggestions.

8.2.1 Lateral movement

The biggest limitations regarding the GaitScanner's movement was that it is restricted to one dimension; i.e. backwards and forwards. This uniaxial movement also makes any deviations more evident as the cannot be correct without manually readjusting the orientation of the GaitScanner. Incorporating lateral movement, such that the GaitScanner is capable of left and right movement would significantly enhance the validity of the captured video footage. Gait assessment test rarely explicitly require subjects to move in a lateral direction however, subjects often cannot maintain a perfectly straight walking trajectory, resulting in undesirable footage.

In recent years there has been great development in unidirectional wheel technology and could also be used on the GaitScanner. Although these wheels may allow for unidirectional movement, much like a regular wheel, they are only actuated along a single axel. Thus, an additional proximity sensor positioned at the sagittal upright position would be needed to sense the lateral distance away from the subject. Much like the current system's mechanism, the additional sensor will maintain a predetermined distance away from the user in the lateral direction controlling a secondary motor and wheel. The proposed system is represented in Figure 8.1 with the colour red representing the existing forward movement and the colour blue representing the added lateral movement.

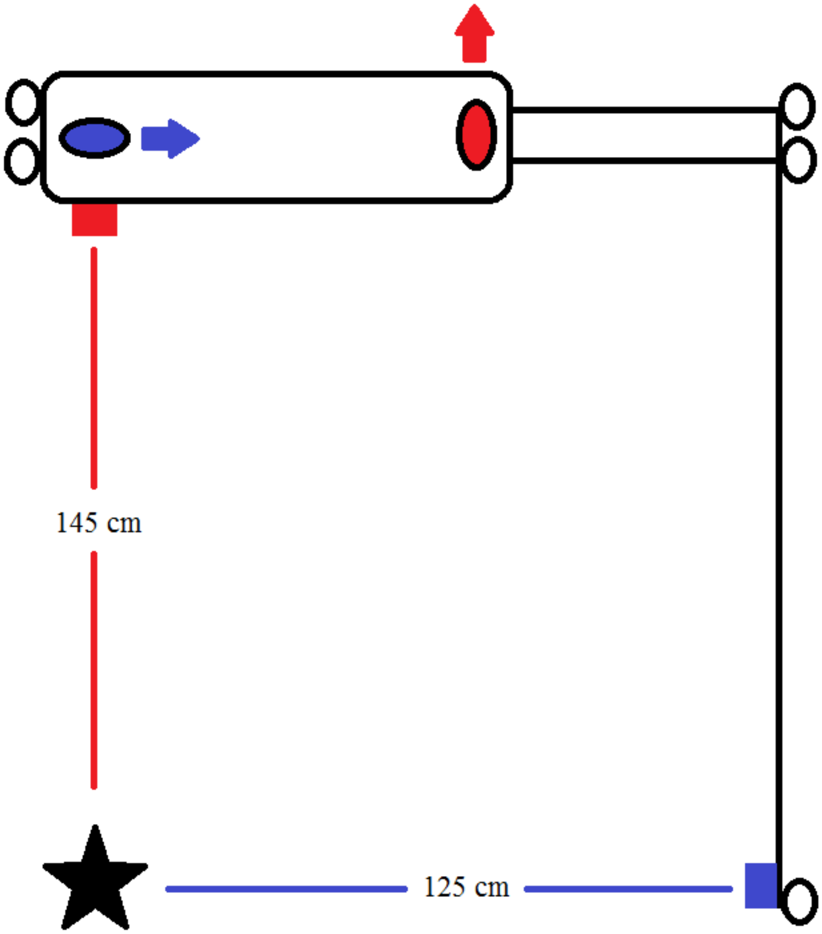

Figure 8.1: Proposed system incorporating lateral movement (represented in blue) in addition to the current GaitScanner movement (represented in red).

8.2.2 Intelligent remote controller

The LCD display on the body of the GaitScanner is relatively small and can be difficult for the operator of the device to see. An intelligent remote controller could be developed, one that not only controls the GaitScanner's menu but also has a display of its own. By having moving the display to remote rather than just on the GaitScanner itself, it provides greater control and assures the user of the function that is currently in operation. Ideally, this remote control display would be in the form of a universal smartphone application that communicates the GaitScanner via Bluetooth. Although this solution has not been fully realised, with some further development this is something that could very well be achieved in the near future will minimal hardware additions to the new GaitScanner prototype.

8.2.3 3-Dimensional gait analysis

The GaitScanner was intentionally developed as a cost-effective alternative to 3-Dimensional kinematic gait analysis. Modern kinematic analysis techniques typically involve contact marker technology with multiple infrared cameras. However, recent advancements in 3D digital image post processing have led to marker-less techniques such as edge detection and stitching multiple 2D videos that could be possibly utilised in future GaitScanner iterations. For these techniques to be employed, a minimum of three cameras are required. The current configuration of the GaitScanner allows for multiple cameras to be mounted to an individual pole but would benefit from a third camera angle. With future development, the GaitScanner has the potential to become a fully autonomous, portable, 3-Dimensional gait analysis device at a fraction of the cost of existing technology.

8.2.4 Commercial kinetic device integration

From the beginning of the project the client has always expressed interest towards commercial kinetic measurement devices, in particularly shoe insole based systems. While no official tests using this hardware has been undertaken in conjunction with the GaitScanner, there seems to be nothing limiting this cross compatibility. From a business standpoint, there may also be an alternate path to market by establishing a partnership with a company who is involved with the development of these commercial insole kinetic measurement systems. Entering a partnership will also presents many challenges, as such this is an option that should only be considered by the client and will be heavily dependent on the direction he is looking to take with the GaitScanner project.

8.3 Final Statement

Thankfully to the efforts of the author, in addition to the guidance and input from the project supervisors and client, all of the project outcomes were able to be accomplished resulting in the successful completion of the GaitScanner project. This biomedical engineering project was a one encompassing a variety of techniques from different disciplines of engineering including mechanical, robotics and software. Although the author experienced some difficulties, the successes achieved throughout the year are testament the manner in which the project was undertaken.

Taking part in a journey spanning over a decade, the essence newest iteration of the GaitScanner can still be traced back to the roots of the project. While the entirety of this device was built upon an existing framework, it takes the aspects and features that made the previous iterations of the GaitScanner great and improves them further to produce the most advanced iteration to date. The intuitive structural design not only provides an enclosure for the electronic components and internal wiring, it expands on the portability by reducing the collapsible size by over 30% when the GaitScanner is not in operation. Prior to this project the GaitScanner did not have a dedicated playback program to view the recorded video footage. With the addition of this program users of the GaitScanner can now simply open the video files using the program, which are then displayed side by side and controlled simultaneously using a single playback control button. The program also has options for inputting notes regarding the patient which can then be exported as a txt file. By having a program such as this video playback GUI the utility of the GaitScanner as a medical device has greatly increased.

This project has involved the development of a portable video gait analysis device that has updated and improved previous iterations by creating a medical device that is capable of autonomous movement, high definition video capture, collapsible structure for portability, emergency stop for objects or walls, a program for straightforward post processing and a user manual with simple instructions. Depending on the future direction of the project the GaitScanner can look forward to success in the marketplace, clinical environment or may even undergo further prototyping. Whichever path it may take the GaitScanner is making the step towards a brighter future in the field of gait analysis.

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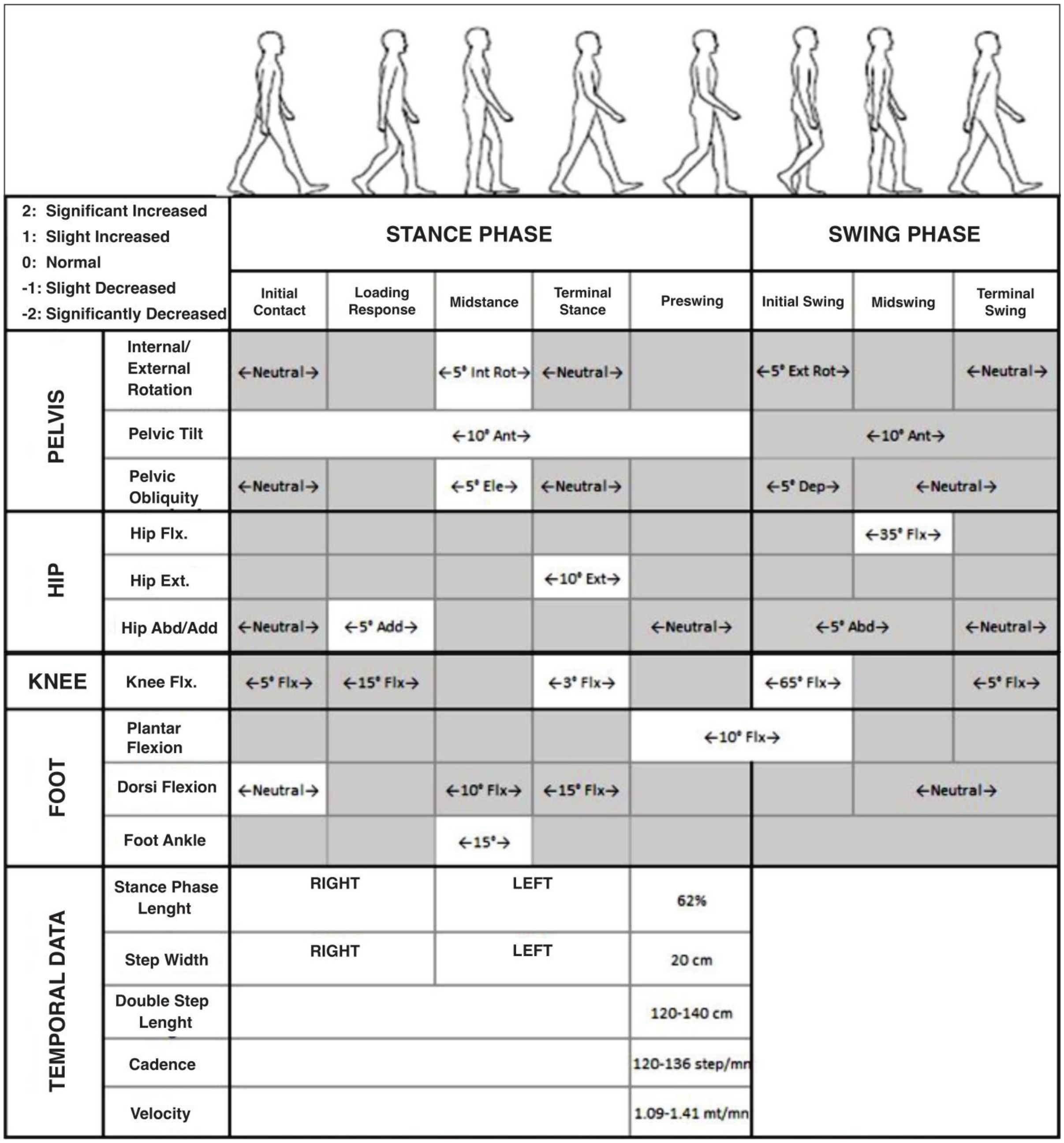
Appendices

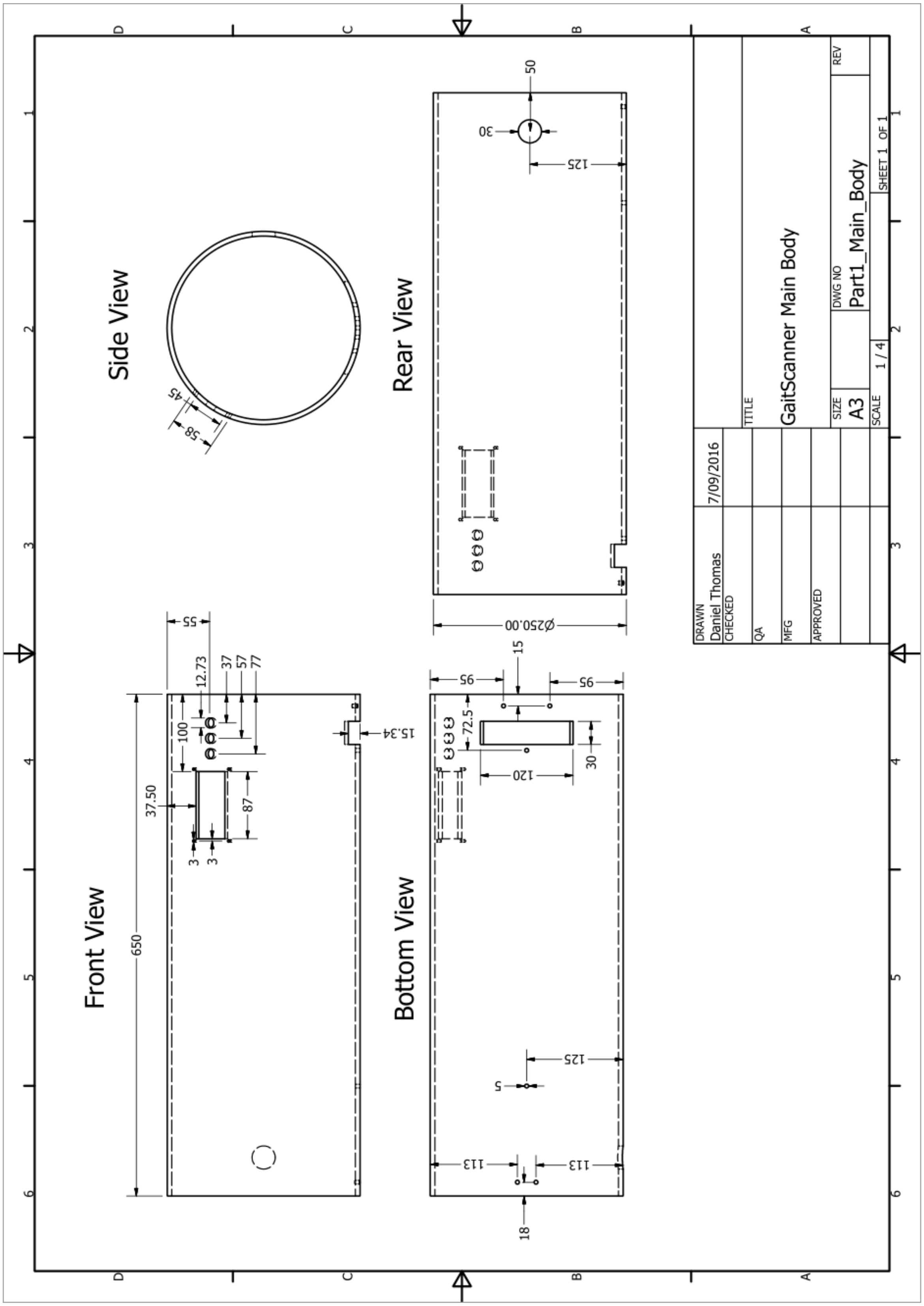
Appendix A

Example OGA form



2: Significant Increased 1: Slight Increased 0: Normal -1: Slight Decreased -2: Significantly Decreased		STANCE PHASE					SWING PHASE		
		Initial Contact	Loading Response	Midstance	Terminal Stance	Preswing	Initial Swing	Midswing	Terminal Swing
PELVIS	Internal/ External Rotation	←Neutral→		←5° Int Rot→	←Neutral→		←5° Ext Rot→		←Neutral→
	Pelvic Tilt	←10° Ant→					←10° Ant→		
	Pelvic Obliquity	←Neutral→		←5° Ele→	←Neutral→		←5° Dep→	←Neutral→	
HIP	Hip Flx.							←35° Flx→	
	Hip Ext.				←10° Ext→				
	Hip Abd/Add	←Neutral→	←5° Add→			←Neutral→	←5° Abd→		←Neutral→
KNEE	Knee Flx.	←5° Flx→	←15° Flx→		←3° Flx→		←65° Flx→		←5° Flx→
FOOT	Plantar Flexion					←10° Flx→			
	Dorsi Flexion	←Neutral→		←10° Flx→	←15° Flx→			←Neutral→	
	Foot Ankle			←15°→					
TEMPORAL DATA	Stance Phase Lenght	RIGHT		LEFT		62%			
	Step Width	RIGHT		LEFT		20 cm			
	Double Step Lenght					120-140 cm			
	Cadence					120-136 step/mn			
	Velocity					1.09-1.41 mt/mn			

Appendix B


Side View
Rear View
Front View
Bottom View
45
58
50
30
125
Ø250,00
55
12.73
37
57
77
100
15.34
37.50
87
3
3
650
15
95
95
72.5
30
120
125
5
113
113
18
DRAWN
Daniel Thomas
7/09/2016
CHECKED
QA
MFG
APPROVED
TITLE
GaitScanner Main Body
SIZE
A3
DWG NO
Part1_Main_Body
REV
SCALE
1 / 4
SHEET 1 OF 1
A
B
C
D
1
2
3
4
5
6

Appendix C

External Media: CAD model files

Appendix D

External Media: MATLAB Code