DEVELOPMENT AND TESTING OF A

GAIT ESTIMATION SYSTEM

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Computing and data acquisition have become an integral part of everyday life. From reading emails on cell phones to kids playing with motion sensing game consoles, we are surrounded with sensors and mobile computing devices. As the availability of powerful computing devices increases, applications in previously limited environments become possible.

Training devices in rehabilitation are becoming increasingly common and more mobile. Community based rehabilitative devices are emerging that embrace these mobile advances. To further the flexibility of devices used in rehabilitation, research has explored the use of smartphones as a means to process data and provide feedback to the user. In combination with sensor embedded insoles, smartphones provide a powerful tool for the clinician in gathering data and as a standalone training tool in rehabilitation.

This thesis presents the continuing research of sensor based insoles, feedback systems and increasing the capabilities of the Adaptive Real-Time Instrumentation System for Tread Imbalance Correction, or ARTISTIC, with the introduction of ARTISTIC 2.0. To increase the capabilities of the ARTISTIC an Inertial Measurement Unit (IMU) was added, which gave the system the ability to quantify the motion of the gait cycle and, more specifically, determine stride length.

The number of sensors in the insole was increased from two to ten, as well as placing the microprocessor and a vibratory motor in the insole. The transmission box

weight was reduced by over 50 percent and the volume by over 60 percent. Stride length was validated against a motion capture system and found the average stride length to be within 2.7 ± 6.9 percent. To continue the improvement of the ARTISTIC 2.0, future work will include implementing real-time stride length feedback.

To my wife and all those who have supported and guided me,
without them this would not have been possible.

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CHAPTER 1

INTRODUCTION

This chapter reviews the previous work that has led to and motivated the research contained in this thesis. The contributions section contains the advancements made with further explanation about those contributions in Chapter 3. Hypotheses tested are stated as well as the means by which they will be tested.

1.1 Previous Work

Previous research includes instrumented shoes, feedback method and IMU data analysis for reducing error in motion tracking, which led to the development of this system.

The general overview described in Chapter 2 gives an understanding of the progression to the current Microelectromechanical System (MEMS) based Inertial Measurement Units (IMU) and also some of the applications where these IMU's are being utilized. The focus was how they are being used to gather data about human motion. While this use is only a small portion of how IMU's are being implemented, it gives an understanding of the type of research being done that is comparable to that explained in this thesis.

The gait analyzing shoe contained accelerometers, gyroscopes, force sensitive resistors (FSR), polyvinylidene fluoride strips, bend sensors, and electric field sensors

[1]. The “gait shoe” was developed to be a system that could give quantitative analysis of a subject’s gait. This type of instrumented shoe offered clinicians a tool to reduce the office time needed to observe the patients gait without the cost of having to go to a motion laboratory. It also allowed for a longer period of data acquisition that could lead to more informed decisions for the patient. The “gait shoe” was also wireless, transmitting data through radio frequencies to a computer where the data could be processed.

Any IMU can be used to find a position by using the gyroscope to relate the IMU’s current reference frame to a global reference frame and then using the accelerometer to determine translation. When those steps are repeated enough times throughout a motion, the position can be followed. To get from IMU data to change in position requires that the gyroscope data be integrated once, and the acceleration data twice, with respect to time. This integration amplifies any noise or bias error that was in the original data. This is even more significant in low-cost IMU’s. Previous studies showed that calibration could reduce a portion of this error, but what reduced the error by a much more significant amount was the state estimation algorithm for rejecting noise and tracking bias [2, 3]. This algorithm greatly reduced the error by finding when the signal was within the noise band of the accelerometer and updating the bias to accommodate for any drift in the signal.

Another precursor to the development of the ARTISTIC 2.0 was research involving feedback. When feedback is presented to the subject based on data gathered, a feedback loop is created allowing the subject to make adjustments and see what effect those adjustments had. The LEAFS, or Lower Extremity Ambulatory Feedback System, used FSRs in silicone insoles to determine the stance time which was then relayed back to the user though a laptop [4]. The ARTISTIC or Adaptive Real-Time Instrumentation System for Tread Imbalance Correction took the feedback, like the LEAFS, but had the feedback come through a smartphone, increasing the mobility and ease of use. The ARTISTIC was the direct predecessor to the ARTISTIC 2.0. The ARTISTIC system utilized a silicone insole that had two FSRs, a 9 volt battery, an Arduino microprocessor, Bluetooth transmitter and an Android based smart phone.

1.2 Contributions

It was observed during the testing of previous feedback systems that while focusing on feedback subject stride length would vary; this, along with the desire to increase the comfort and data acquisition capabilities brought about the decision to add an IMU and upgrade the ARTISTIC system to the ARTISTIC 2.0. The contributions made are listed below with a more in-depth presentation found in Chapter 3.

Hardware

- Increasing battery life
- Incorporating IMU
- Redesigning transmission box
- Increasing the number of sensors
- Placing arduino microprocessor in insole
- Adding vibrotactile motors

Software

- Using I^2C communication
- Organizing and sending data
- Controlling vibratory motor l
- Developing IMU data processing to average stride length
- Applying average stride length function to phone

1.3 Hypothesis Tested

In order to quantify the effectiveness of the changes made to the ARTISTIC in the development of the ARTISTIC 2.0 the following Hypotheses were tested.

- Hypothesis 1- Reducing the size and mass of the ARTISTIC and increasing the capability will be correlated with an improved level of comfort. The level of comfort will be determined from the surveys taken by the subjects after each test.
- Hypothesis 2- Stride length can be measured within 10 percent of a motion capture laboratory and will vary when feedback is applied. The stride length error will be measured by the step length measured by the ARTISTIC 2.0 and that of the motion capture laboratory. Stride length variance will be determined by comparing the average stride length during a baseline walk without feedback and while feedback is being presented.

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CHAPTER 2

IMU HISTORY

2.1 Introduction

This chapter reviews the background and progression of Inertial Measurement Units. It reviews the components and explains how they function. An overview of research systems and implementation that relate to this thesis are also presented.

2.2 Inertial Measurement Units

Inertial measurement units (IMUs) have been around since the 1920s, but the introduction of MEMS (Microelectromechanical System) has opened up many new applications for such devices. Over the last few years, MEMS-based accelerometers and angular rate sensors have become part of everyday life for most people. Accelerometers can be found in everyday items such as automobiles, cell phones, and video game systems such as the Nintendo Wii. Angular rate sensors, also known as gyroscopes, have also increased in application, being used in commonly used items such as video cameras or computer mice. An IMU most commonly consists of three orthogonal accelerometers and three orthogonal gyroscopes.

2.2.1 Accelerometers

The first commercialized accelerometers were introduced by McCollum and Peters in the early 1920s. They weighed almost a pound and were 0.75 x 1.875 x 8.5

inches in size and made of an E shaped frame using 20 to 55 carbon rings in a tension compression Wheatstone half bridge. These first accelerometers were used primarily for vibration detection and recording in such places as bridges, underground pipes and turbines. Because of the ongoing Depression, there was not a widespread use of accelerometers. The advancement and use of accelerometers took place mainly in large companies and within government research using accelerometers to test acceleration during such things as drop tests of airplanes.

Accelerometers were not readily available until the late 1930s with development of the strain gauge which resulted in the strain gauge accelerometer. There were problems with these early strain gauge accelerometers though. Since the full range of the signal output was approximately 30 mV, the signal to noise ratio was low. Depending on material used, the resonant frequency could be low, limiting the use in measuring high frequency vibration, with a maximum around 200 Hz. These units weighed approximately 2 oz.

The next step in accelerometer development came around 1950 with the development of piezoelectric accelerometers. Piezoelectric accelerometers were an improvement with a linear response up to 10,000Hz. The sensitivity of these accelerometers was 35-50 mV/g with resonant frequencies up to 35 kHz and weights from 2.5 to 52 grams.

Up until the early 1990s the advancement of accelerometers came in the form of improved piezoelectric accelerometers, primarily in terms of size, temperature stability, increased resonant frequency, and measurement range. In 1969, a 1.3 gram, 100,000 **g** rated and 250,000 Hz resonant frequency piezoelectric accelerometer was developed by Endevco.

In 1991, the next big step in accelerometer development came with the introduction of Microelectromechanical Systems (MEMS) accelerometers. Initial MEMS accelerometers were still piezoelectric, but they used surface micro manufacturing techniques used in producing microchips to not only increase the volume production capability, but also decrease the size of the accelerometer. The ADXL50 accelerometer, commercially available in 1993 from Analog devices, was 5mm square [1]. Later, accelerometers featured adjustments such as tap sensing, interrupts and selectable measurement range. The ADXL345 (Analog Devices, Norwood, MA), available in 2011, is 3 mm x 5 mm x 1 mm with three orthogonal axes of measurement.

Currently, accelerometers are being used in many different applications, including fall detection. Jay Chen used accelerometers attached to the waist of a subject along with determining the acceleration that would normally occur throughout an individual's day to send an alert for help if an acceleration threshold was supposedly indicating a fall. He found that the overall magnitude in his system that indicated the fall of an elderly person was 6.9 **g** or above [2].

Another area where accelerometers have been used is to help improve swimming technique. Marc Bachlin created a system that uses accelerometers on the upper and lower back to detect body rotation as well as accelerometers on the wrists to detect the number of strokes. The idea behind this system is to help improve swimming technique by improving stroke efficiency and reducing drag. Drag increases if the body is rotated in the wrong orientation and stroke efficiency goes down if the arms are not going through the correct motion. The system uses accelerometers to detect points in the motion and determine markers such as the number of strokes and when the swimmer has reached the end of the pool and turned around. The swimmer is then returned visual and auditory feedback based on the found markers, length of the pool, and time to help improve the swimmer's technique [3].

2.2.2 Gyroscopes

Gyroscopes are physical sensors that detect and measure angular motion of an object relative to an inertial frame of reference. There are two types of gyroscopes: rate gyroscopes measure the angular velocity or rate of rotation and angle gyroscopes measure the angular position or orientation. There are also angular acceleration sensors but these are not as common. Almost all MEMS gyroscopes measure angular velocity. Early work of gyroscopes in the mid-19th century was done by Leon Foucault. He approached the gyroscope design by either having a spinning mass or a vibrating mass that allowed for the rate of rotation detection. The prominent design was based on a spinning mass until the second half of the 20th century but was not well suited to MEMS because of manufacturing constraints. Building low friction bearings is difficult using MEMS processes and levitation of a mass is still being explored [4]. This pushed the gyroscope development in MEMS devices to use the vibrating mass. When an angular rate is applied to a body, a Coriolis force is generated, which can be measured. Most MEMS gyroscopes use silicon structures suspending arms that create a resonating tuning fork when a voltage is applied. When an angular rate is applied, a proportional Coriolis force distorts the resonating tuning fork. This distortion can then be measured by a change in capacitance or piezoelectric change depending on the materials used [5, 6].

2.2.3 MEMS Devices

The use of MEMS devices provided advantages beyond what was currently produced. The first advantage was the size. The production of MEMS devices is done much like other semiconductor industries by multiple etching, doping, and diffusing processes on and in silicon substrate. The structure dimensions are determined by a mask that allows light to convert photoresist into a protective pattern, allowing for etching or other processes to make the pattern that was dictated by the photoresist. This process allows for structures down to the micro level and is only limited by the level of clean room and the wavelength of light. MEMS inertial measurement structures can be under 1 mm square [5]. Another advantage of MEMS production is that because of the size there is the possibility of constructing hundreds of devices on a single production wafer, decreasing cost and increasing availability. There are other advantages in MEMS devices such as lower power consumption while still achieving the durability needed for many environments [7].

Accelerometers and gyroscopes combined with MEMS technology, that reduces the size of these tools, have greatly increased the availability and applications. Accelerometers alone are a very powerful tool. In smartphones multi-axis accelerometers can be used for tilt detection based on the direction of gravity to change screen orientation or to determine a shaking motion in an application. Gyroscopes are used in smart automotive steering and in camera-stabilization equipment. While accelerometers and gyroscopes can be effectively utilized individually, when combined into an IMU the applications and information that can be provided are increased. One of those uses is to determine changes in position and orientation.

2.3 IMU Studies

Researchers have been very creative in combining different devices to make up the necessary components for making and using an IMU, such as in the paper "Wearable indoor pedestrian dead reckoning system" by Jorge Torres-Solis and Tom Chau [8]. This study used a Nintendo game console or Wii remote controller, computer mouse, portable camera and a small form factor computer to develop an economical dead reckoning system. A dead reckoning system is one that can determine position by estimating direction and velocity over time, in this case using angular velocity and acceleration to determine position. The goal of this dead reckoning system was to use mainstream hardware components. The computer mouse was attached to the waist of a subject and contained a dual axis gyroscope that was used to detect a heading. The Nintendo Wii controller has a three axis accelerometer that is used to determine the length of each step. The portable camera was attached to the shoulder to recognize predetermined markers along the subject's path and take into account any accumulated errors. The data from each device was sent to the computer where the position was calculated. Initially the system contained additional mechanical footswitch sensors in the shoe that detected when the foot was down. During these still periods a zero velocity update was applied to the accelerometers to take into account any drift in the bias that may have occurred. Due to a failure in the mechanical switch the accelerometers were used to detect this still period. The total cost of the sensors for the system was 150 dollars.

Another study involved the use of IMUs in devices we carry with us such as a cell phone or be able to place an IMU in different locations on the body and still be able to gather data about the individual's gait. One complication is that the characteristics of the IMU data will differ depending on its location on the body. The desire of the research was to monitor a subject and able to determine if a specific person was carrying the device [9].

There has been an increasing amount of research using MEMS based IMU's to study human motion and even more specifically the human gait. The level of accuracy possible has been sufficient to find the differences in the gait cycle of particular populations [10] .

There have been a number of systems that utilize an IMU in combination with other sensors to reduce error accumulation. Another study using an IMU in combination with a camera is the vision-inertial self-tracker (VIS-Tracker) developed by Foxlin [11]. The VIS-Tracker is made up of an IMU and camera in one unit that is 55 mm x 27 mm x 15 mm and weighs 35grams with an attached power supply. The VIS-Tracker is then attached to a hat for use in navigation. Foxlin placed emphasis in the calibration of the camera to be able to align the IMU and camera information. Like the above mentioned system, the VIS-tracker requires previously placed markers to determine the location of the subject. While this system does utilize an IMU, the IMU is only a secondary navigation device determining position between markers and allowing the camera to be the primary navigation sensor.

Foxlin has also done other pedestrian tracking that uses an IMU, magnetometer and a Gobal Positioning System (GPS) for assisting in long distance tracking and navigation. The sensor package, called the InertiaCube3, is attached to the shoe and transmits the data through Radio Frequency (RF) to a computer where it is analyzed. In this system the IMU is the main navigation tool, with the magnetometer used to compensate for any error in heading, and the GPS adjusting for long range error. The system also uses zero velocity updating to reduce error in the accelerometer data [12].

The availability and small size of current IMU's has made data acquisition much easier than in the past. ETHOS is a self-contained IMU (developed by Holger Harms) small enough to be able to attach to cloth and gather data about human movement. ETHOS is 14 mm x 45 mm x 4 mm and contains an accelerometer, gyroscope, magnetometer, microprocessor and a micro SD card for data storage. Much of the research performed by Harms was to extend battery life while still having a significant amount of data. The sampling rate and filtering methods were adjusted during testing to determine the impact made to the battery life [13].

While navigation systems that include both an IMU and other sensors have their place, they also have other complications. The previous three studies used IMUs in combination with other sensors. When using a camera in combination with an IMU the system uses a known area, with previously placed markers the camera can recognize. A camera also requires much more information to process. If a "smart camera" is used, where some preprocessing can be done by the camera, the markers must be detected by the camera, which, when placed on a subject could be a source of error depending on marker density in the navigation area and the pixel count of the camera. If a magnetometer is used as a secondary sensor there are other complications. When a magnetometer is used in combination with an IMU, the magnetometer is used to determine heading. The gyroscope is often utilized in measuring higher rates of rotation and the magnetometer for lower rates of rotation. The magnetometer is also used to compensate for bias drift. While the magnetometer can detect the earth's magnetic field it can also be affected by ferric materials that could disturb local magnetic and local magnetic fields such as those created by electrical wiring throughout a building [14]. Foxlin noted that an IMU alone could not be used for pedestrian tracking beyond a few seconds [12].While systems using combined sensors with IMUs can increase accuracy there is also the introduction of other forms of error.

To help eliminate the need for additional sensors, research is being done to reduce error in IMU alone systems. Anthony Kim has worked with correcting orientation drift due to the gyroscope. He used Quaternion-based orientation estimation, which is a common way of determining the reference frame from gyroscope data, in conjunction with his developed Kalman filter to better follow the any gyroscope drift [15].

Within the Bioinstrumentations Lab at the University of Utah it has been shown that with the correct data processing, an IMU can be sufficiently close for determining position with error as little as 40 mm over a 30 second time period [16-18].

Another sensor unit that is being used in research is the S-Sense. The S-Sense has a three axis gyroscope and a three axis accelerometer, and is 57 mm x 41 mm x 19.5 mm. It has a sampling rate of 200 Hz and a max data transfer rate of 625 kbps. The S-Sense was designed to attach to the foot and give information about the gait cycle. The walking phase detection algorithm program on the S-Sense is primarily to determine when the foot was down [19]. The S-Sense detected 93.2 percent of the footsteps with no false positives and of those not detected, half were either the first or last step.

The S-Sense was then used in combination with motorized training shoes to gather information on possible clues for understanding what aspects of gait may lead to an increase in instability [20]. Each motorized shoe is comprised of two actuators in the toe and two in the heel, with a binding to hold the actuators to each other and to the subjects shoe with the S-Sense attached to the heel of the motorized shoe. The S-Sense was used to determine when the foot was on the ground and then the motorized shoe would produce unpredicted perturbation during the stance phase to force the subject to adjust their balance. The system as a whole was used to gather data about instability and as a training tool.

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CHAPTER 3

ARTISTIC 2.0

3.1 IMU Incorporation

Because of the redesign necessary to add the IMU, the entire insole and electronics box were redesigned. The IMU has a three-axis accelerometer and a three axis gyroscope that uses I^2C communication. The first aspect that was addressed was the placement of the IMU. Because of the sensitivity of the IMU to vibration, a relatively stable location was desired. Even wiring that could transmit external movement to the IMU was taken into account. The IMU was placed in the insole itself, which put the IMU in almost direct contact with the subject's foot, which is what is being observed. Because the IMU is in the insole, it is insulated from some vibration by the silicone and also held firmly in place by the foot on top and the shoe underneath, eliminating external vibrations due to wiring or to excess movement of the IMU housing.

3.2 Battery Power

Battery life in the ARTISTIC 2.0 was an area of concern because of the increase in the number of sensors, and because the original ARTISTIC battery life was lower than desired. Because the battery was also the heaviest of any component, a reduction in weight was also desired. The novel concept of using a cell phone battery was pursued which not only improved upon the two areas above but also other aspects of the design.

The selected Lithium-Ion cell 3.7 v phone battery (Part # AB653850CA Nexus S) has an increased capacity of 165 percent compared to the 9 v battery used previously, and a 50 percent reduction in weight. Using the cell phone battery, the estimated working time is 16 hrs. Along with the reduction in weight the slim profile of the cell phone battery allows for a more compact transmission box. Another advantage is that the cell phone battery is rechargeable, eliminating the need to buy other batteries, and is charged using the cell phone charger.

3.3 Additions to Insole

One side effect of the battery change was that a 3.3 v Arduino Mini was used instead of the previously used 5 v Arduino Mini. However, the need for voltage adjustment by the Arduino was reduced, and combined with the overall lower operating voltage make the system more power efficient. In the ARTISTIC, the Arduino was in the transmission box, which was appropriate because it was then close to the power supply and Bluetooth transmitter with only four wires going to the insole connecting to the FSRs. With the ARTISTIC 2.0 the four wires would become 10 to connect the IMU and using the original two FSRs. Instead, the location of the Arduino was moved to the insole, as shown in Figure 3.1. This reduced the number of wires between the transmission box and insole to eight. The components left in the box were the battery, connectors, switches, and the Bluetooth transceiver, which was left in the box to avoid signal interference from the foot. A vibratory motor was also added to the box so that a subject with a lower limb amputation would be able to move the box to a location on the body that has sensation to receive vibrotactile feedback. Moving the Arduino to the insole

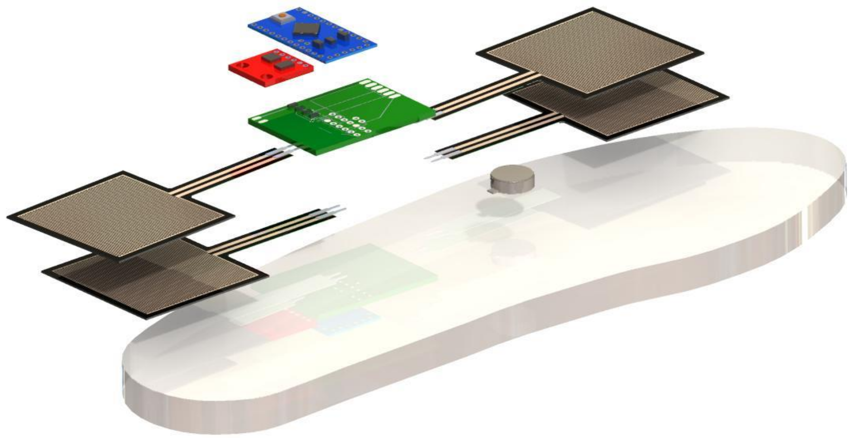

Fig. 3.1: ARTISTIC 2.0 insole components

also opened up the possibility of adding more sensors and components without the penalty of an increased number of wires leaving the insole.

To further increase the capabilities of the insole a second set of FSRs, and a vibratory motor were added to the insole. The purpose of adding two more FSRs was to make the insoles as versatile as possible. The insole then had two 1.5 inch square FSRs stacked on each other under the toe and two under the heel. Studies have shown that FSRs can reliably be used as a switch to detect when the foot is down [1] but this is dependent upon the resistor that is used in the voltage divider with the FSR. The response curve of the FSR to the force input can be manipulated for a more linear output at different sections of the curve by changing the resistor in combination with the FSR. In the ARTISTIC 2.0 a 5 kΩ resistor was chosen to have a curve that spikes quickly, creating a pressure switch type of performance. For a better estimation of force a 1 kΩ resistor was used in the second set of FSRs to give a slower response. A vibratory motor was placed in the insole to give flexibility in the location that a subject could receive vibrotactile feedback.

3.4 Transmission Box

To give a mounting place for sensors and to organize the electronic wiring, two printed circuit boards (PCB) were designed. One was for the insole and the other for the transmission box. The PCB for the insole provided a mounting location for the IMU, Arduino, resistors for the FSRs, and pads to attach the FSRs. This board was designed to be in the low pressure area under the arch of the foot. This proved to be a comfortable configuration for the subjects as well as a protected area for the circuitry, with no failures occurring during testing because of damaged PCB, IMU or Arduino. The PCB designed for the transmission box served as a secure location for mounting the connector for the insole and Bluetooth transmitter as well as soldering points for the vibratory motor and battery wiring.

Because of the changes in the location and types of components, a new transmission box was designed and printed on a 3D printer. The transmission box, as shown in Figure 3.2, was designed to hold the battery securely, while allowing the battery to be changed without affecting any of the other wiring. The battery was also used to help stiffen the structure of the box. This allowed the box to be reduced in size and weight. The box also included strategically placed clasps to hold the PCB board and tie-down straps without needing additional fasteners. The hardware comparisons can be found in Chapter 4 of this thesis.

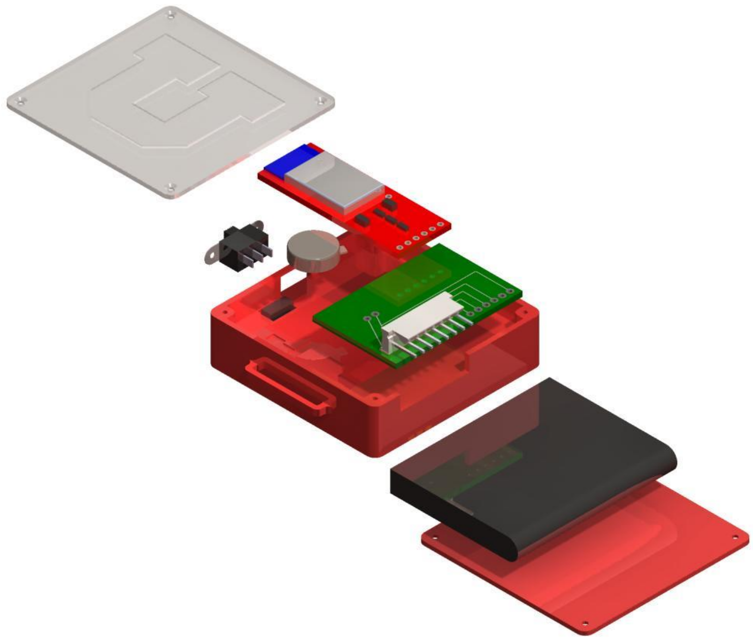

Fig. 3.2: ARTISTIC 2.0 transmission box components

3.5 Arduino Software

Another major contribution is code for the Arduino to control the sensors and components, and for the smartphone for the IMU data processing to find the stride length.

The program on the Arduino was required to accomplish a few key tasks. One was to communicate with the IMU through I^2C communication, also known as a two-wire interface. The use of I^2C communication allowed the six IMU sensors to be read using two analog ports, leaving the remaining ports for the FSRs. The I^2C works by having master and slave devices. In this case, the Arduino was the master and the gyroscope and accelerometer in the IMU were the slaves. For the master device to gather a reading from any of the slave devices a series of communications must be performed to open communication: call for a reading to be sent, receive the reading, and then close communication with that slave device. While the communication does take a series of steps, those steps have not been a limiting factor in this system. This type of communication also enables “smart” sensors. When the program first starts, the IMU slave devices must be set up by a few commands. These setup commands can take advantage of an adjustable setting available in the devices. For example, the accelerometer used has an adjustable range from ± 2 g’s up to ± 8 g’s, and both the accelerometer and gyroscope have power saving settings. While there is more involved with this type of communication, the increased availability of ports and flexibility in settings of the sensors make it a worthwhile choice.

The program also had to read in all of the other sensor values as well as record the time interval between each reading cycle. Next the program had to send that data through the Bluetooth transmitter to the smartphone. The Bluetooth communication was aided by the use of a toolkit called Amarino that is specifically designed to aid in the communication between Arduino microprocessors and Bluetooth-enabled Android platforms [2]. The program had to listen for a flag sent from the smart phone to turn on or off the vibratory motor used for feedback to the subject. While preforming all of these functions the Arduino program maintained a sampling rate of 90 Hz.

The main objective of the Arduino was to gather data and send it to the smartphone. Then on the smartphone the data was processed, used for feedback, and stored. One aspect of that processing was to use the IMU data along with the time interval to determine the stride length.

3.6 IMU Processing

With a future goal of providing real-time feedback about stride length to the user it was important to find a balance between the computational cost and the amount of error involved in the algorithms used. One way to reduce the processing power needed was to use two-dimensional position estimation instead of three-dimensional. Three-dimensional position tracking involves taking into account the bias of the six sensors, and required more complicated matrix mathematics. This two-dimensional process simplified the motion to a single plane, assuming that significant rotation was about the Y axis and significant translation in the X and Z directions. This assumption had been used with good results in past work [3].

Even with the two-dimensional assumption, there would still have been a significant amount of error introduced due to bias drift, so zero velocity updates were used to track the bias. Zero velocity updates used the stance time period, when the velocity is known to be zero to track the bias of the accelerometer and gyroscope. Previous work has shown that still periods can be found using the IMU data and then updating the bias [4]. The process requires that additional calculations be done on every point to determine the still periods. To simplify the introduction of stride length estimation to the ARTISTIC 2.0, instead of using IMU to determine the still periods, the FSRs at the heel and toe were used to determine the stance time period. Traditionally, the bias updates during one stance time would be used at the bias for the following swing period. To further reduce error, the bias before and after each swing period was used to interpolate the bias during the prior swing period allowing for the bias to be more closely followed, as in the work done by Eric Johnson [5]. Specific equations used, images and flow diagrams can be found in Chapter 4.

The position change of each step was calculated with an assumption of the subject walking on a level surface. An average position change was then reported for the entire trial.

All testing, development and verification of the system was done in Matlab® by uploading the data from the phone. The verification results can be found in Chapter 4.The mathematical functions available within Matlab® reduced the amount of time necessary for changing the code during development and allowed for increased visibility of the data throughout each step. To use the same functions on the smart phone the process needed to be converted into Java. Java does not have the same mathematical or matrix manipulation functions that Matlab® does, so the used functions were created or simplified into multiple equations for use in the Android application.

3.7 References

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CHAPTER 4

A MOBILE GAIT TRAINING SYSTEM PROVIDING REAL-TIME FEEDBACK THROUGH SMARTPHONE TECHNOLOGY

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4.1 Introduction

Gait rehabilitation is used to eliminate or reduce gait pathology. An asymmetric gait that remains uncorrected has the potential to cause balance impairment, metabolic costs, osteoarthritis, and lower back pain. Gait rehabilitative methods tend to be highly specialized for the individual patient [1], causing a high resource demand throughout rehabilitative therapy. Current equipment used for real-time gait retraining is typically large, stationary, and expensive [2-4]. Due to high demands for personnel and equipment during rehabilitation, many efforts have been made to design more mobile gait rehabilitation devices [5-7].

Embedded system technology has allowed for the creation of body-wearable sensor networks for remote health and activity monitoring. These networks have the potential to enhance quality of life, facilitate independent living, and reduce rehabilitation resource demands [8]. Smartphone and tablet technology is becoming increasingly pervasive as more devices are introduced to the market. There is a need for systems that connect body-wearable networks with the processing power and storage capacity of mobile devices such as smartphones and tablets.

4.1.2 Motivation

The need for an inexpensive, truly mobile gait rehabilitation device spurred the development of the Adaptive, Real-Time Instrumentation System for Tread Imbalance Correction (ARTISTIC). This device interfaces body-wearable embedded systems with smartphone technology. One of the primary goals of this device was to provide three different modes of real-time feedback (visual, auditory, and vibrotactile) about gait symmetry through a smartphone application (app) [9]. The first design of the ARTISTIC was validated in a study of subjects with healthy, normal gait. The majority of subjects from the study preferred the visual feedback mode and all subjects were able to significantly alter their gait in response to the visual feedback [10]. The auditory and vibrotactile feedback modes were perceived as difficult to use. These modes provided only a binary reactive response indicating whether the prior two steps were above or below a specified symmetry threshold. Furthermore, it was reported that the communications box attached to the subject's ankle was heavy and caused discomfort. The first design was also limited to measuring only stance time characteristics.

This paper presents development of the revised ARTISTIC device that implements proactive auditory and vibrotactile (haptic) feedback modes. The system incorporates a tri-axial accelerometer and gyroscope to measure and analyze more gait parameters simultaneously. System verification against current clinical gait measurement technology is provided. Findings from a validation study involving subjects with prosthetic gait are also presented and discussed.

4.2 Novel System Design

The ARTISTIC design was revisited and critical changes were made in all aspects of the design. The next sections discuss design improvements in the device hardware and software. In this paper, the revised version will be referred to as ARTSITIC 2.0.

4.2.1 Hardware

The ARTISTIC 2.0 hardware consists of three primary components: an instrumented insole, a communications box, and a smartphone. Design priorities for each component included keeping the system simple, intuitive, inexpensive, and robust.

4.2.1.1 Instrumented Insole

Previous designs of instrumented insoles involved an array of force sensitive resistors (FSRs) embedded in silicone with other electronics housed in a separate container or box [9]. Our novel insole design embeds an inertial measurement unit (IMU) and a microprocessor in addition to FSRs as shown in Figure 4.1.

Since FSR responses vary depending on the value of the resistor in their voltage divider circuit [11], two 1.5” square FSRs (Interlink Electronics, Camarillo CA) were stacked in the toe and heel regions of the insole to track different types of data. One FSR in the toe and one in the heel made up a pair. One pair of FSR voltage dividers used 5kΩ resistors to capture heel-down and toe-off characteristics like a footswitch [12]. The other pair used 1kΩ resistors to take readings with more resolution to be used in determining plantar pressure [11].

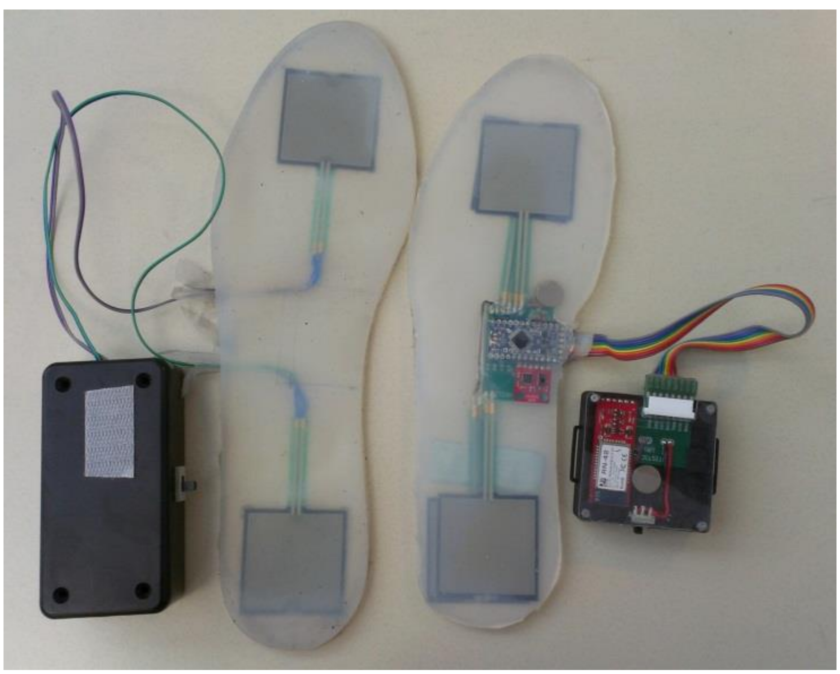


Fig. 4.1: ARTISTIC and ARTISTIC 2.0 systems (left to right)

Previous studies using an IMU for gait measurement placed the IMU on the back of the shoe or in a separate box [13, 14]. Two problems arise from positioning the IMU like this. First, the box is rigidly mounted to the shoe and is difficult or impossible to use on other shoes. Second, excessive movement not associated with the actual gait is recorded by the IMU, making it more difficult to go from acceleration to position. Here, the IMU, a combination board of an ITG3200 gyroscope (InvenSense Inc, Sunnyvale, CA) and an ADXL345 accelerometer (Analog Devices, Norwood, MA), was embedded in the insole to reduce noise and to simplify transfer of the system to different shoes.

An Arduino Pro Mini microcontroller (Sparkfun Electronics, Boulder, CO) with ATMEGA 328 (Atmel Corp, San Jose, CA), 8MHz microprocessor was used to sample data. Since the Arduino needed to connect to FSR, IMU, Bluetooth, and vibro motor components, embedding the Arduino in the insole reduced wire lead lengths. It also reduced connections that could be severed by repetitive flexion and pressure from the foot. To further reduce the number of wires and component sizes, a printed circuit board (PCB) was designed for the ARTISTIC insole. The Arduino, IMU, and PCB are depicted in Figure 4.2.

Embedded inside the insole is a VPM2 vibrating disk motor (Solarbotics, Calgary, Canada). This actuator can be used to deliver vibrotactile haptic feedback. The motor is connected to a digital output pin on the Arduino.

4.2.1.2 Communications Box

The instrumented insole requires power and a means of data transfer from the Arduino to the Android smartphone. The insole is connected to the communications box, which transmits data wirelessly using Bluetooth protocol. To provide power, the

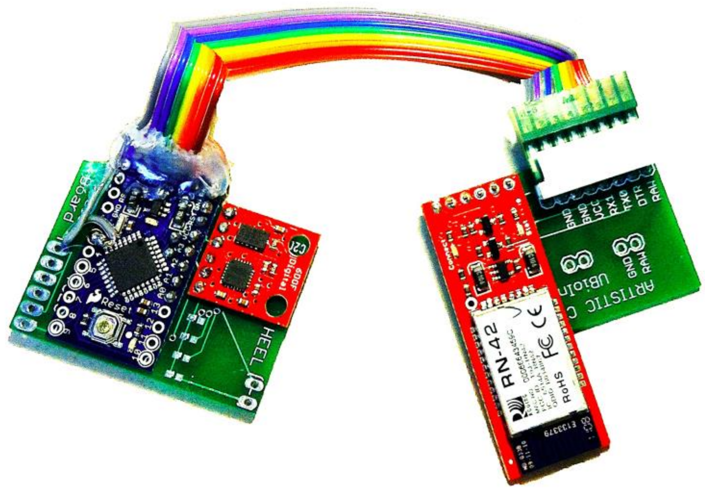


Fig. 4.2: PCB boards with Arduino, IMU, and Bluetooth modem mounted to them

communications box houses a rechargeable 3.7 Volt battery providing 1500 milliamp hours of power. For data transmission the communications box includes a Bluetooth Mate Silver Class 2 Bluetooth modem (Roving Networks, Los Gatos, CA), transmitting at 57.6 kbps. The Bluetooth Mate Silver consumes about 50 milliamps when transmitting data and only 25 milliamps when idle, regardless of the connection status [15].

To simplify connections between the Arduino and Bluetooth Mate, a PCB was also designed for the communications box. The PCB is shown in Figure 4. 2 with a Bluetooth Mate mounted to it. The communications box included a VPM2 motor identical to the one embedded in the insole. This motor is also connected to a digital output pin on the Arduino through the PCB board. The purpose of placing a motor in the communications box is to provide haptic feedback to individuals who cannot feel an insole vibration because they have prosthetic feet or suffer from peripheral neuropathy. The assembled communications box is shown in Figure 4.3.

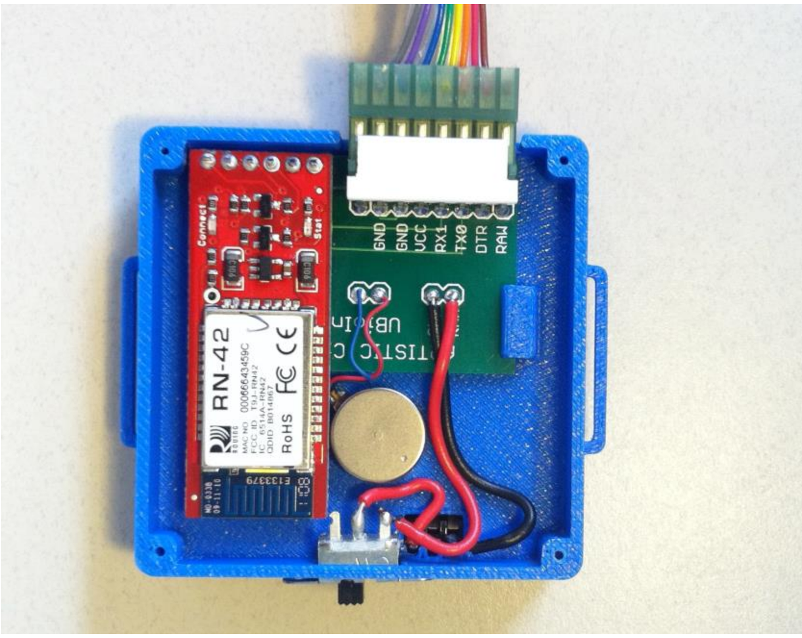


Fig. 4.3: Communication box showing Bluetooth modem, PCB, and vibrating motor

Key improvements in the communications box and ARTISTIC 2.0 system as a whole are presented in Table 4.1. Weight and volume of the communications box decreased while number of sensors, data rate, and power supply were significantly increased.

4.2.1.3 Smartphone

It is projected that nearly 1 billion smartphones will be in use worldwide by 2015 [16]. Additionally, use of tablets and similar devices running on smartphone platforms is on the rise. Therefore, it is not unreasonable to propose a smartphone-driven rehabilitative device, because patient access to a smartphone, or smart device can be generally accepted. The ARTISTIC 2.0 uses a Samsung Nexus S smartphone (Samsung, Seoul, South Korea) running the Android 2.2 platform (Google, Mountain View, CA). The Nexus S has a 1 GHz processor and 16 GB of internal memory. It is important to

Table 4.1 System comparison between ARTISTIC and ARTISTIC 2.0

Specifications:	ARTISTIC	ARTISTIC 2.0	% Change
Weight (g)	103.5	51.3	-50
Volume (mm3 x 103)	150.6	49.6	-67
Sensors (qty)	2	10	+400
Data Rate (Hz)	5	90	+1700
Power Supply (mAh)	565	1500	+165

note that each smartphone running an Android platform will have unique processor and storage specifications dependent on the manufacturer and model. An Android smartphone was selected as the platform for development because Android follows the Open Handset Alliance, allowing for unrestricted development on any Android device.

4.2.2 Software

Data transmission between the Arduino microcontroller and the Android smartphone required software development in two different environments. Processing the data from the IMU required development of a Java library to be run on the Android smartphone.

4.2.2.1 Android

An extensive Java based application (app) was developed for the ARTISTIC 2.0. The app utilized the computing power of the Android smartphone to take in large amounts of raw data, process them, and provide feedback to the user.

To interface between the Arduino and Android, ARTISTIC 2.0 used an open-source toolkit developed by Bonifaz Kaufmann called Amarino [17]. This toolkit provided an Android app and an Arduino library to make interfacing simpler for developers by providing pre-written code to run the Android-Bluetooth protocols.

The ARTISTIC 2.0 app received Bluetooth signals at 180 Hz (two signals, one from each limb at 90 Hz). Each signal contained 11 different data points. The Android thus processed over 1900 individual data points per second. Raw data was used to calculate important gait parameters and also stored for post-processing. Data was stored and retrieved as text files using the internal storage techniques native to the Android platform. Feedback was provided through the smartphone based on the gait parameters calculated during on-phone data processing. A visual representation of data handling on the smartphone is given in Figure 4.4.

4.2.2.2 Arduino

The Arduino integrated development environment utilizes C++. An infinite loop was created to poll all sensor readings, measure the time to complete polling, and transmit readings through the Bluetooth modem as concatenated strings. The loop also contained a function that would listen for a message from the Android with instructions

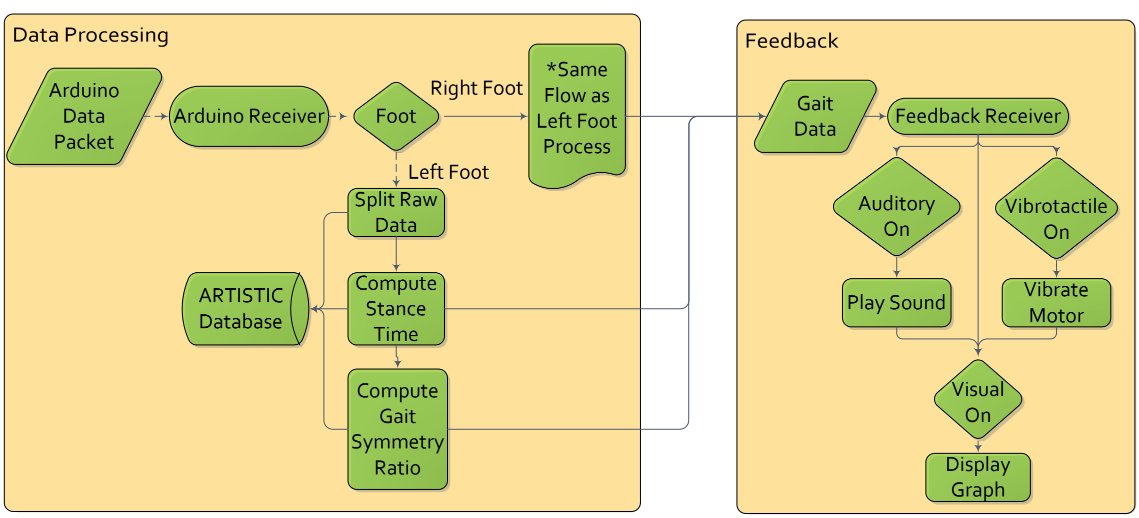


Fig. 4.4: Flowchart of data processing and feedback decisions in Android smartphone app

to send signals to the VPM2 motors in the insole or communications box. Data transmission through the Bluetooth modem was accomplished using the MeetAndroid library, which is part of the Amarino toolkit [17]. Sensor polling and data transfer are shown in Figure 4.5.

4.2.2.3 IMU –Java library

To work with the data from the IMU and compute the stride length, a Java library was developed for use in the Android app. Functions within the library read in the data from a walking test, identified the important markers from each step, and calculated the average distance travelled for each step from toe-off to heel-down.

4.3 Methods

Data obtained from the FSR and IMU sensors were processed on the phone to compute gait characteristics of stance time, symmetry ratio, and stride length. Resulting values were used to provide feedback to ARTISTIC users.

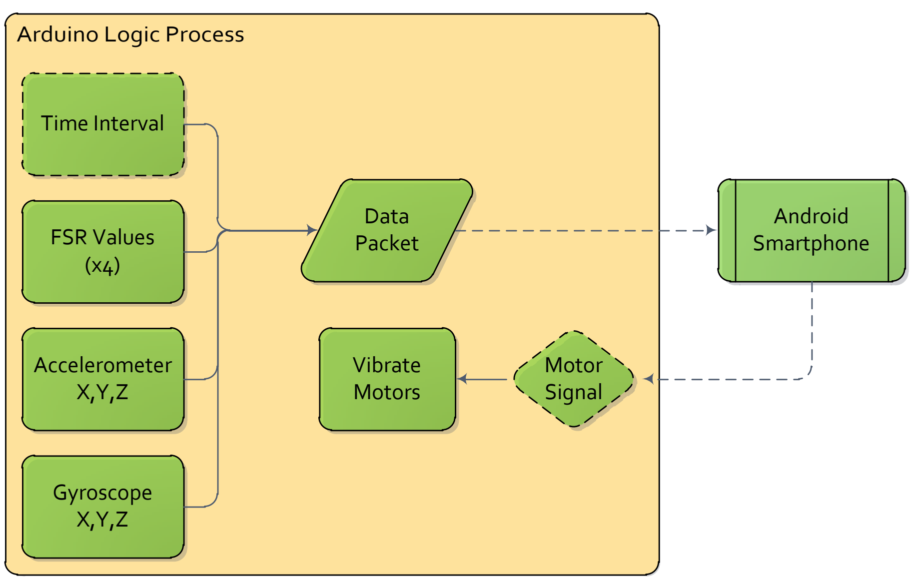


Fig. 4.5: Flowchart of sensor polling logic process occurring on Arduino microprocessor

4.3.1 Sensors

4.3.1.1 Force Sensitive Resistors (FSR)

Voltage changes across the FSRs were sampled by the Analog to Digital converter (ADC) on the ATMEGA328 chip. The ADC had 10-bit resolution. The resulting digital output values were used to analyze stance time and symmetry ratio measurements. With no weight on the insole the FSR output values typically have a non-zero bias. This bias is a reflection of pre-loading on the FSRs, e.g. caused by the tightness of the shoe on the foot. The bias varies each time the ARTISTIC is setup. Therefore, a calibration routine was included in the Android app to "zero" the output values. To determine gait flags such as heel-down or toe-off, a threshold for the output values was set for each FSR as follows.

$$GaitThreshold = 0.5 * (MaxValue_{FSR} - Bias_{FSR}) + Bias_{FSR} \tag{1}$$

The algorithm used by ARTISTIC 2.0 to determine stance time is outlined in Figure 4.6. Stance time on the ARTISTIC 2.0 is defined by the equation below.

$$t_{stance} = t_{toe\_off} - t_{heel\_down} \tag{2}$$

Stance time for each foot was used to compute gait asymmetry. There are several methods to compute gait asymmetry [18]. The method selected for ARTISTIC 2.0 is the symmetry ratio.

$$Symmetry\ Ratio = \frac{t_{paretic}}{t_{non\_paretic}} \tag{3}$$

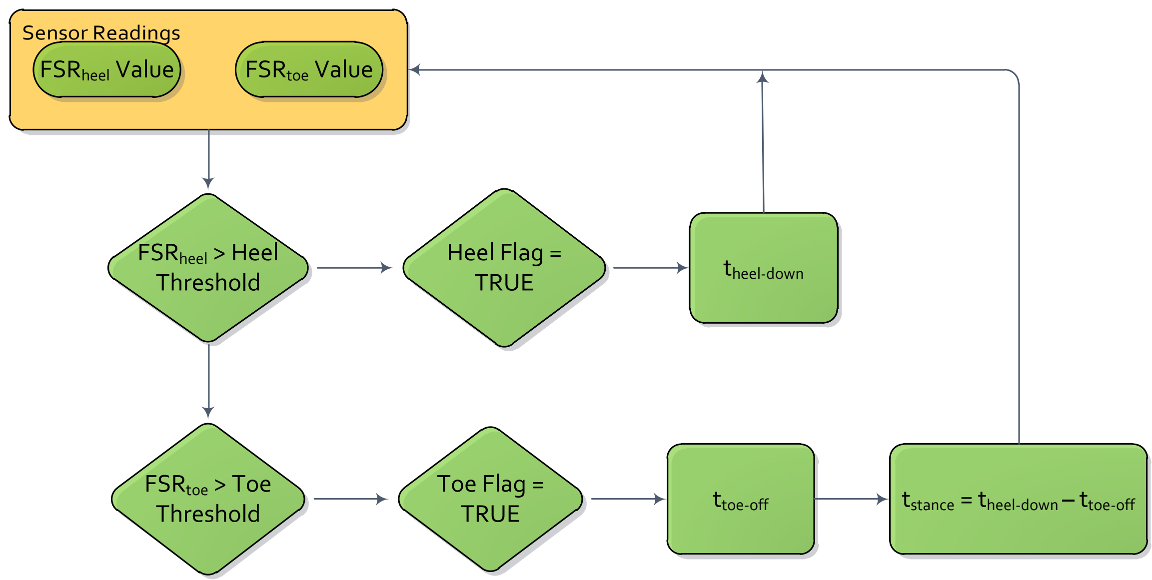


Fig. 4.6: Algorithm used by ARTISTIC 2.0 to calculate stance time

Where $t_{paretic}$ represents the stance time of the less favored limb, a prosthetic limb for example, and $t_{non\_paretic}$ represents the intact or favored limb. To make the symmetry ratio simpler, the ARTISTIC 2.0 algorithm ensured that the numerator was always the lesser of the two stance time values. A negative sign was used to indicate asymmetry favoring the left leg and a positive sign indicated asymmetry favoring the right leg. It was possible for the symmetry ratio to change from positive to negative within a single trial. This also made statistical analysis more powerful because the ratio was no longer skewed by values > 1.0 [18].

4.3.1.2 Inertial Measurement Unit (IMU)

The tri-axial accelerometer and gyroscope on the IMU communicate with the Arduino through I^2C protocol. The accelerometer was set at ±2*acceleration of gravity (*g*) along each axis with a sensitivity of 256 LSB/*g* and the gyroscope has a range of

±2000°/sec with a sensitivity of 14.375 LSB per °/sec. Both were sampled by the ADC, which has 10-bit resolution.

There are two coordinate systems used for computation of the IMU data as shown in Figure 4.7. The first is the global reference frame where the user is walking. The second is the body frame, which is the frame of the insole itself, where the IMU is mounted. The body frame reflects the orientation that the sensors are reading within. In order for the stride length to be calculated, the acceleration readings need to be transformed from the body frame into the global frame.

To simplify and speed up computation, movement of the foot was assumed to occur only in the X-Z plane with rotation occurring only about the Y-axis in the body frame. Subjects were instructed to walk in a straight line. A previous study under similar conditions found that the angular velocities about the Z and X-axis and the acceleration

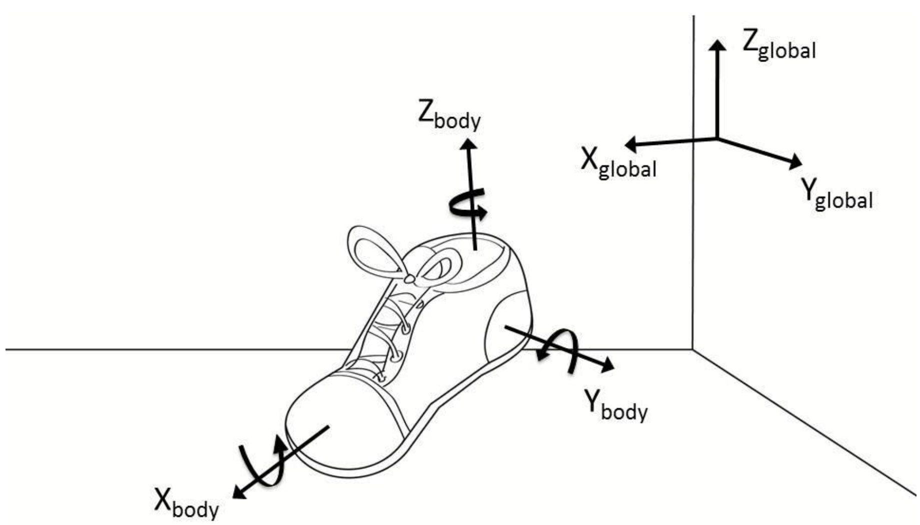


Fig. 4.7: Two reference frames used for IMU computation

along the Y-axis were much lower, making this a reasonable assumption for stride length estimation [14]. Rotation matrices were used to transform the readings from the body frame to the global frame. To compute the rotation matrices, the rotational velocity about the Y-axis of the body was integrated to get an angle of change at each time step. The equation used is

$$\theta_{i+1} = \left[\frac{(\omega_{i+1}+\omega_i)}{2} \times (t_{i+1} - t_i)\right] + \theta_i \tag{4}$$

After determining the angle of rotation at each time step a rotation matrix was computed and used to transform the acceleration reading in the equation

$$\begin{pmatrix} X_{Global} \\ Y_{Global} \end{pmatrix} = \begin{bmatrix} COS(\theta) & -SIN(\theta) \\ SIN(\theta) & COS(\theta) \end{bmatrix} \begin{pmatrix} X_{Body} \\ Y_{Body} \end{pmatrix} \tag{5}$$

Because of the inherent drift in both the accelerometer and the gyroscope, Zero Velocity Updates [19] were incorporated using the cyclic nature of walking. The bias was updated during a detection period of zero velocity, after the acceleration due to gravity was removed. The zero velocity period of a step was identified when both the heel and toes sensors register force indicating that the foot is in contact with the ground. The gravitational acceleration was removed and the remaining acceleration readings during this time were taken as the bias of the accelerometer giving a bias for each axis to be taken into account over the next step. To further improve upon the bias updating, the functions use not only the bias at the beginning of a step but also the end of the step allowing for a linear bias adjustment over the time of the stride.

To detect when the foot is at rest (zero velocity) or when the foot is in swing, the FSR readings are used along with calibrated threshold of the FSRs to find the heel-down, toe-down, heel-off and toe-off gait flags. With these points identified for each step, the bias update can take place from toe-down to heel-off followed by the double integration of the acceleration between toe-off to the next heel-down. A diagram of how the IMU data is processed is shown in Figure 4.8.The equation used for integration is

$$v_{i+1} = \left[\frac{(a_{i+1}+a_i)}{2} \times (t_{i+1} - t_{i})\right] + v_i \tag{6}$$

4.3.2 Feedback

The gait characteristics measured by ARTISTIC 2.0 are relayed to the user through three feedback modes. Each mode was designed to be simple to interpret by the senses it targeted.

4.3.2.1 Visual Feedback

The user interface for ARTISTIC 2.0 visual feedback provides graphical and numeric feedback to the user, as seen in Figure 4.9. Two vertical gray lines indicate an acceptable gait range (+0.8 to -0.8 with 1.0 at the center). This gait range is a variable

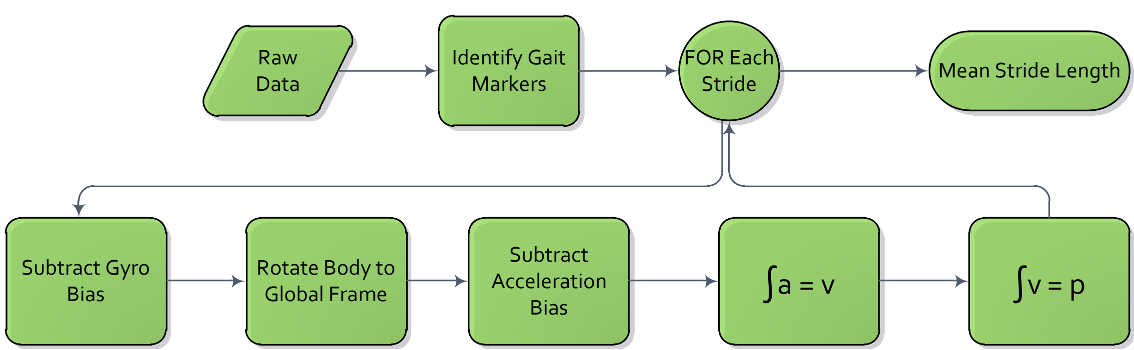


Fig. 4.8: Flowchart of IMU data processing

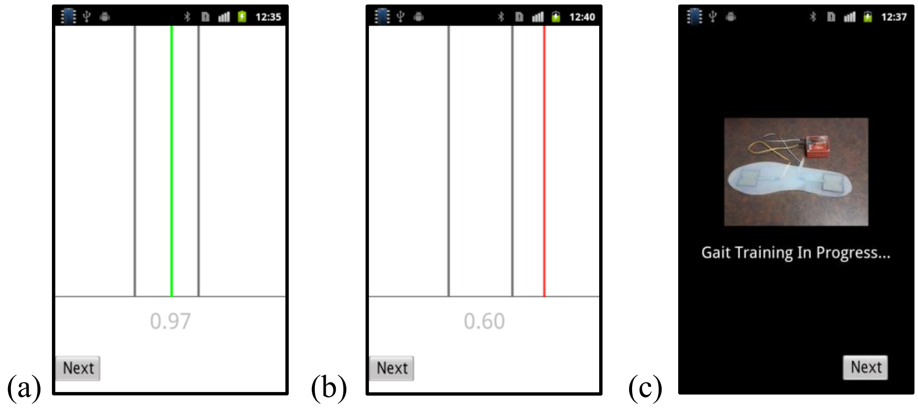


Fig. 4.9: Screenshots from ARTISTIC 2.0 app during visual (a and b) and nonvisual (c) feedback modes

that can be set as a target zone for the user to achieve depending on the severity of the user's gait asymmetry. A third vertical line, the "gait marker", indicates the user's current symmetry ratio and is updated each time a step is taken. If the current symmetry ratio falls within the acceptable gait range the gait marker is displayed in green. When the symmetry ratio leaves the acceptable gait range the gait marker is displayed in red. Gait marker placement to the left of the gait range lines indicates more time spent on the left leg. Placement to the right indicates more time on the right leg.

The symmetry ratio is displayed numerically at the bottom of the screen. Positive and negative signs are not displayed here to reduce confusion about meaning of the signs. Indication of direction for asymmetry is delivered through location of the gait marker instead.

Movement of the gait marker is intuitive because its position corresponds with the leg that is being favored and it provides negative feedback when the marker turns red. Numeric values are easy to interpret because they tend towards 0.0 as gait becomes less symmetric and towards 1.0 as gait symmetry improves.

4.3.2.2 Auditory Feedback

It is believed that reaction times to auditory stimulus are faster than reaction times to visual stimulus [20, 21]. Most studies on auditory feedback use either a pre-selected metronome speed or a subject-preferred speed, based on the most comfortable walking pace for the subject, in an open-loop feedback model [22-24]. However, closed-loop feedback has been shown to regulate and stimulate gait improvements more than open-loop feedback [25].

Design of the ARTISTIC 2.0 auditory feedback targeted a closed-loop method. The continuously updating metronome is dictated by an average of the previous 10 stance times from both feet. The average stance time is used as the desired stance time for the next step. This makes the auditory feedback closed-loop as shown in Figure 4.10. A continuous average of stance times allows auditory feedback to update real-time to keep up with changes in the subject's gait such as increases or decreases in walking speed.

The auditory feedback played a tone during the final 300 milliseconds (ms) of the desired stance time. The moment at which auditory feedback began was calculated as follows

$$t_{tone\_start} = t_{heel\_down} + (t_{desired\_stance} - 300\ ms) \qquad (4)$$

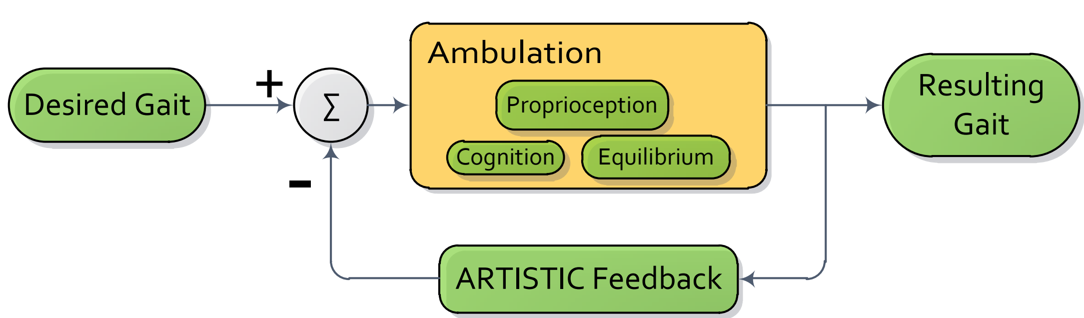


Fig. 4.10: Closed-loop feedback as provided by ARTISTIC

Repetitive auditory stimuli can become less effective in arousing the perceptual process over time [25]. To break up the repetitive nature of the auditory feedback, the first five tones from the diatonic scale of C are played as feedback tones. With each successive step the next tone in the scale is played, repeating the pattern every fifth step, thus creating a melody. The goal for subjects during auditory feedback is to keep the tones in rhythm by walking symmetrically.

4.3.2.3 Vibrotactile Feedback

The smartphone display during vibrotactile feedback uses the same static image and message used during auditory feedback (Figure 4. 9). Vibrotactile is a form of haptic feedback. Studies have shown that haptic feedback results in better tracking and subjective estimation of movement than visual feedback [26, 27]. ARTISTIC 2.0 vibrotactile feedback is provided by the VPM2 motors in the insole and communications box.

Vibrotactile feedback on the ARTISTIC 2.0 system uses the same timing algorithm as the auditory feedback for determining desired stance time and the start time of feedback cues. During the 300 ms of a vibrotactile feedback cue, the selected VPM2 motor vibrates. Toe-off should occur when the vibration ceases.

4.3.2.4 Stride Length Feedback

Stride length is computed at the conclusion of each feedback session on the ARTISTIC 2.0. This gives the user needed information to determine if their stride length should be adjusted during the next session. Implementing the stride length feedback at the end of the session does not interfere with needed smartphone resources, which could disrupt the time-sensitive feedback methods already discussed.

4.3.3 Subject Testing

Human subject testing was carried out to validate the ARTISTIC 2.0 device in a clinical setting. The testing protocol was approved by the University of Utah Institutional Review Board under the study no. IRB00053021. Ten subjects were recruited through the Department of Physical Medicine and Rehabilitation, University of Utah Hospital. All subjects had a lower limb prosthetic on one limb. The subjects were aged 48 ± 24 years. They were 5 feet 9 inches ± 3 inches tall and weighed 195 ± 46 pounds. Six of the subjects were male and four subjects were female. Six subjects had undergone an amputation of their right leg while four subjects had undergone an amputation of their left leg. Of those amputations, eight of them occurred below the knee while only two occurred above the knee. All subjects provided approved consent prior to testing.

Subjects were asked to participate in several short walking cycles during the course of testing. The testing protocol was designed to assess the ARTISTIC 2.0 system's ability to influence individual gait. Testing was also designed to determine the corresponding effectiveness of the visual, auditory, and vibrotactile feedback modes. Each subject was first introduced to the system and Android application interface. The subject was provided instructions on how to follow the different feedback cues and interact with the Android application. Installation of the ARTISTIC 2.0 was demonstrated and then subjects were instructed to install the system in their own shoes. Communication boxes, used to power the system and transmit wireless signals, were attached on top of the shoelaces with Velcro as in Figure 4.11.

Fig. 4.11: Subject wearing ARTISTIC 2.0

Following initial setup, each subject was asked to walk to the end of a 150-foot hallway and return to the starting point. The total distance walked was about 300 feet. During this baseline walk, no feedback was provided but data was collected on the Android smartphone for a control comparison with subsequent walks. After the baseline walk the subject completed three more walks of equal length to the baseline during which visual, auditory, or vibrotactile feedback cues were provided through the ARTISTIC 2.0. Selection of the feedback mode to follow was randomized using a balanced latin square. Upon completion of the three walks with feedback, the subject was asked to select two preferred modes of feedback. During a fourth walk the two preferred feedback modes were enabled in parallel to provide a combined feedback mode. Finally, the subject completed one more baseline walk with no feedback to assess whether any residual effects existed from the feedback modes.

After testing was complete, subjects filled out a questionnaire about their experience interacting with the ARTISTIC 2.0. The questionnaire was designed to gain insight into the possibility of the ARTISTIC 2.0 being used as a rehabilitative device that could be used outside a clinical setting. Subjects answered questions about their comfort level while wearing the device, their perceived stability during testing, and the efficacy of different feedback modes in altering their gait.

4.3.3.1 Statistical Procedures

Raw FSR data from each trial was analyzed post-testing to determine stance time, symmetry ratio, and stride length values. To determine the correlation between preferred feedback mode and changes in gait characteristics, the mean values from each subject's preferred feedback mode were compared against the control or first baseline walk using a two-tailed, paired student's t-test. Mean values from a feedback mode that produced the largest change in gait symmetry were compared to the control walk using the same two-tailed t-test. If the preferred method produced the largest change, the feedback mode that produced the second largest change was analyzed. Mean values from each subject's last baseline walk were also compared to their control walk using the same t-test. Based on results from the t-tests, p-values under 0.05 were considered statistically significant. Following the statistical tests, a post hoc power analysis was performed on the results of the t-tests. The post hoc powers are reported with the statistical results.

4.4 System Verification

4.4.1 Approach

To confirm the validity of the system, the ARTISTIC 2.0 was verified against equipment in the Motion Capture Laboratory of the Department of Physical Therapy, University of Utah. Motion capture in 3D was accomplished using a ten-camera Vicon motion analysis system (Centennial, CO) and two AMTI multi axis force platforms

(Watertown, MA). Multiple sets of data were captured using the motion capture systems and the ARTISTIC 2.0 in parallel.

Verification of stance time measurements was accomplished by comparing stance times computed from the ARTISTIC 2.0 with stance times determined by pressure readings on the AMTI multi axis force platforms. Stance time on the ARTISTIC 2.0 were marked as FSR readings crossed threshold values set by an initial FSR bias reading, as described in Section 3.1.1. Stance time on the AMTI force platform was marked when pressure readings were non-zero. The AMTI force platform data capture rate was 1000 Hz. Time on the ARTISTIC 2.0 was recorded as time differences between data transmissions from each Bluetooth modem. Data was captured using both the 1kΩ and 5kΩ voltage divider circuits in the ARTISTIC 2.0.

To validate the stride lengths processed by the ARTISTIC 2.0, the stride length was first calculated using data from the motion capture system. To do this, the minimum value in the Z-direction reached by each step interval was determined. Then, using those times as the beginning and end of each step, changes in the X and Y-directions were used to determine the total change in position from each step. Computation of total change utilized the Pythagorean Theorem. The IMU data was processed as described in Section 4.3.1.2.

4.4.2 Verification Results

Analysis of ARTISTIC 2.0 stance times showed that the system was capable of determining stance time within a 7.8 ± 1.0 percent difference from the force platforms if the system is utilizing the 5 kΩ voltage divider circuit for FSR readings. Utilizing the 1 kΩ voltage divider circuit results in a 13.5 ± 3.3 percent difference. The 5 kΩ circuit is more accurate in determining stance time because its FSR readings respond quickly to pressure but also saturate quickly. Alternately, the 1 kΩ circuit provides greater resolution in FSR readings as they correspond to foot pressure because it takes more pressure to saturate the readings. Both circuits were included in the ARTISTIC 2.0 design to provide for more flexibility in measurements. Results are presented in Table 4.2.

The stride length measurements from the Artistic 2.0 were evaluated using methods previously described. Stride length measurements were found to have an average error of -2.7 ± 6.9 percent as compared to the Vicon system. Results of the test are presented in Table 4.3.

4.5 Results

Subject testing of the ARTISTIC 2.0 was completed with ten subjects. During testing, data storage was inconsistent for three of the subjects. Therefore, test results were only analyzed for seven subjects. However, feedback functioned during testing for all ten subjects. As such, results of the usability questionnaire were reviewed for all ten subjects.

Table 4.2 Stance time comparison between motion capture equipment and ARTISTIC 2.0

Test	Resistor Type	FP Stance Time (s)	FSR Stance Time (s)	Error (%)
1	1k	0.793	0.668	-15.8
2	1k	0.795	0.661	-16.9
3	1k	0.933	0.831	-10.9
4	1k	0.902	0.807	-10.5
			Average	**13.5 ± 3.3**
5	5k	1.006	0.934	-7.2
6	5k	0.919	0.856	-6.9
7	5k	0.860	0.783	-9.0
8	5k	0.839	0.770	-8.2
			Average	**7.8 ± 1.0**

Table 4.3 Stride length comparison of the motion capture system to the ARTISTIC 2.0

Test	Motion Capture (mm)	ARTISTIC 2.0 (mm)	Error (%)
1	1269.1	1216.4	+4.10
2	1342.9	1234.7	+8.10
3	1235.5	1227.1	+0.7
4	1253.9	1243.6	+0.8
5	1235.9	1367	-10.7
6	1245.4	1399.5	-12.4
7	1234.9	1290.6	-4.5
8	1245.4	1356.9	-8.9
9	1152.4	1205.6	-4.4
10	1206.1	1309.9	-8.6
11	1219.1	1261.1	-3.5
12	1224.4	1135.7	+7.2
		Average	**2.7 ± 6.9**

During testing, subjects reported an inability to perceive the vibrotactile cues. As a result, the last two subjects tested were not asked to walk with the vibrotactile feedback mode turned on. Analysis of stance time and gait ratio results excluded the vibrotactile datasets for all subjects except subject seven, who selected vibrotactile and auditory modes for the combined feedback trial.

Analysis to determine if the altered gait symmetry ratios were statistically different from the control is presented in Table 4.4. Average gait symmetry ratios over five trials are presented graphically for one subject in Figure 4.12a.

Results of the post-testing questionnaire indicated that 40 percent of the subjects selected the visual feedback mode as their favorite, 30 percent selected auditory, and 30 percent selected combined auditory and visual. When asked if the feedback modes made a noticeable difference in their gait, 60 percent agreed that the visual mode was effective,

Table 4.4 Statistical significance of feedback modes (p-values < 0.05 were considered statistically significant)

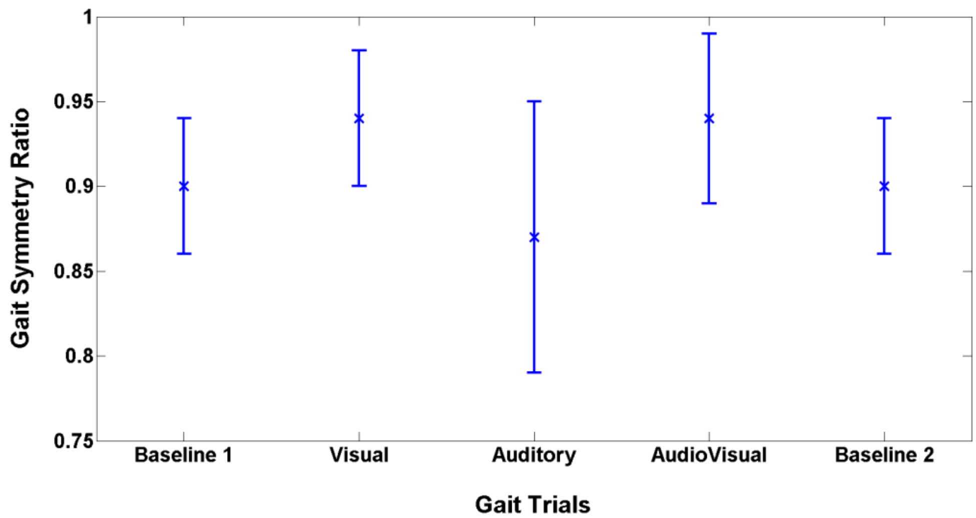
Feedback Mode	p-Value	# of Subjects	Power
Gait Symmetry Ratio			
Preferred	**0.014***	6	0.84
Largest Non-Preferred Change	**0.021***	6	0.75
Baseline 2	0.099	5	0.30
Stride Length			
Preferred	**0.019***	6	0.78
Largest Non-Preferred Change	**0.034***	6	0.64
Baseline 2	0.080	5	0.43

50 percent agreed that the auditory mode was effective, and 50 percent agreed that the combined auditory and visual mode was effective. Only 10 percent of subjects felt that their stability worsened while wearing the ARTISTIC 2.0, but 70 percent were willing to take the system home and wear it for up to three days.

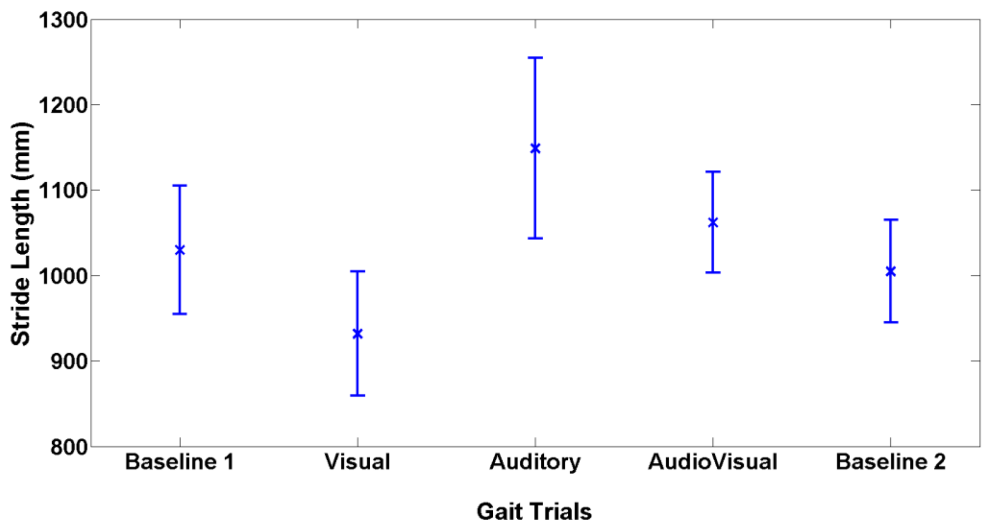
Analysis of stride lengths showed that subjects took steps between 700mm to 1400mm long. Average stride length of an individual subject varied between feedback mode trials. An example of average stride lengths is provided for one subject in Figure 4.12b.

4.6 Discussion

The ARTISTIC 2.0 system was effective in modulating the gait of subjects with a lower limb prosthetic during an extremely short training process as compared to normal gait rehabilitation. This result suggests that the system may be capable of positively adjusting the gait of a rehabilitative patient if used during more extensive and longer training periods. Use of the ARTISTIC 2.0 required little specialized training and all



(a)



(b)

Fig. 4.12: Attributes of a subjects' gait that were captured through the ARTISTIC 2.0. (a) gait symmetry ratio and (b) average stride length of subject 9 over five trials

subjects agreed that they were able to walk and move normally with the system installed in their shoes. Most subjects agreed that setting up the system on their own would not be difficult. This demonstrates that the ARTISTIC 2.0 is a simple, modular alternative to gait retraining using specialized equipment and environments. The system is also an economic alternative to more expensive gait analysis equipment, with an estimated prototype cost of US$345. It also indicates that the system is a viable option for at-home rehabilitation.

The *p*-values calculated indicate that what subjects selected as preferred feedback modes were effective in altering the gait symmetry of subjects. There was no preferred feedback mode that was an overwhelming favorite among the subjects. The preferred method selected by subjects did not correlate with the method that best altered their gait. This suggests that perception of an intuitive feedback mode is more influenced by individual preference than results of that feedback mode. Although subjects selected a preferred mode of feedback the majority of subjects also agreed that non-preferred feedback modes were effective.

Variance in gait symmetry ratio and stride length displayed an inverse correlation. As gait ratio improved, stride length decreased. This is an indicator that subjects began focusing more on following feedback cues and less on moving from one location to another. Furthermore, effectiveness of feedback cues can be determined, in part, by analyzing stride length during a feedback mode trial. If stride length decreases, the feedback mode likely interrupted the subject’s perceptual process, which is the first step in providing feedback that works well with the senses.

One subject reported feeling that their stability worsened while wearing the ARTISTIC 2.0. In the post-testing questionnaire this subject stated that more practice with the combined visual-auditory mode could produce better results. This statement indicates that learning to follow the feedback cues was difficult for this subject and could have caused unstable gait.

Although the ARTISTIC 2.0 altered gait symmetry during a short testing period, the changes were relatively small. These findings correlate with those of the original ARTISTIC system that large permanent gait corrections must be made gradually [10]. This study was conducted among a small subject population but has built upon results from the previous ARTISTIC system. Testing needs to be completed with larger numbers of subjects interacting with the ARTISTIC 2.0 for a matter of hours or even days, preferably in the home environment. Further system improvements include installation of stronger vibrotactile motors in the communications boxes or embedded in the insoles that will be felt by subjects. This is necessary to be able to validate the vibrotactile feedback mode.

Another improvement is creating a more reliable connection between the communications box and insole. Wires and soldered connections were severed various times during subject testing, rendering subject data unusable. One possible alternative to these inconsistent connections is the long-term goal of embedding the system battery and Bluetooth modem inside the insole alongside the Arduino microcontroller and IMU. This would further simplify the ARTISTIC system as a whole, eliminating external wires and making system setup quicker.

During testing, the bias value of some FSRs had a tendency to drift either high or low. One possible cause of this drift is that silicone ran into the FSR pad while curing during manufacture of the insoles. Future revisions of the system should create a verification process to determine tendency of the FSR bias to drift in an insole.

System improvements also include changes to the Android smartphone application. For example, a SQLite database was developed to store raw values in real-time on the Android smartphone but was not successfully implemented during this study because it kept crashing the app due to the high storage volumes required every second. Optimization of the storage process should be assessed to implement this database in further revisions. Data capture through the app did not stop between tests, resulting in large amounts of data that was discarded post-testing. This data collection was using processing power unnecessarily. Later revisions of the application will eliminate periods of unwanted data collection and storage.

4.7 Conclusion

A mobile gait rehabilitation device using real-time feedback was developed for gait correction and training. The system was shown to record stance time and stride length with a maximum error of 17 percent as compared to equipment in a motion capture laboratory. The system was determined to be effective at altering the gait symmetry of subjects ambulating with lower limb prosthesis. Tests performed indicated that no single feedback mode was more effective than another. Instead, subjects identified with different feedback modes on an individual basis. The custom Android application, developed to process data and provide feedback, demonstrated its power as a mobile computing alternative to laboratory equipment or even laptop computers.

Use of this system may be extended to rehabilitation of subjects who have suffered from a stroke or Parkinson's disease. The system can serve as a supplemental rehabilitation device both in a clinical setting as well as for personal assistive healthcare. To further develop this device we will improve the vibrotactile feedback mode and make efforts to embed the power source and wireless communication board in the instrumented insole portion of the system.

4.8 Acknowledgements

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CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This thesis documented the advancement of the hardware and software of the ARTISTIC to the ARTISTIC 2.0. The ARTISTIC moved the data processing and feedback output to a mobile smartphone running an Android application. The ARTISTIC 2.0 embodies another step in mobile gait training by increasing the amount and type of data gathered along with additional types of feedback.

The system was upgraded by adding an IMU, additional force sensors, vibratory motors, PCB boards, and increased power supply. Also, the microprocessor was moved to the insole. The transmission box mass was decreased by 50 percent and volume reduced by 66 percent. Stride length feedback was introduced to the system by the use of the IMU data and functions developed for the Android application. The Java functions used provide a concise way to estimate stride length feedback while preparing the way for future use in real time feedback.

The following hypotheses were also tested:

- <u>Hypothesis 1</u>- *Reducing the size and mass of the ARTISTIC and increasing the capability will be correlated with an improved level of comfort.* The subjects that used that ARTISTIC reported discomfort in the hardware and mounting. No subjects that used the ARTISTIC 2.0 reported discomfort. The statement response used within the survey to determine comfort level was, “Comfort level changed with system in shoes.” The average response was a 1.9 out of 5 showing little change in the comfort level when compared to the subject’s shoes and showing that there was an improved level of comfort.

- Hypothesis 2- *Stride length can be measured within 10 percent of a motion capture laboratory and will vary when feedback is applied.* The step length determined by the ARTISTC 2.0 was compared to a motion capture lab. The average error over twelve steps was -2.7 with a standard deviation of 6.9 percent with a maximum error of 12.4 percent. While the maximum was beyond the hypothesized value, the average stride length was within the 10 percent stated. It was found that during testing there was differences in stride length with and without feedback as described in Chapter 4.

5.2 Future Work

While the ARTISTIC 2.0 system has increased in capability and is able to estimate stride length, there are future steps that can be taken.

Because of the desire for comfort, the insole connections and wires were all kept as small as possible. When the subjects placed their feet on top of the insole inside their shoe, there was a significant amount of strain placed on the wires and connections coming from the insole. With repeated use the wires would fray, introducing power loss. A new connection type that would not be obtrusive but more resilient would increase the durability of the system as a whole.

Another area that could be improved upon would be step detection. The process for determining bias updates, integration period, and the number of steps is based upon the reading of the FSRs. This occasionally created a situation that a step was detected by a shift in weight, but without corresponding movement, or where the signal did not transition well to determine the step marker that was used for analysis. This could be overcome by using the IMU to find the still periods, marking when the foot was down, eliminating the need for input from an alternate sensor. The change in position processing would then be independent for the force measurements. This would allow the two sensor types to be checked against one to another to form an additional layer of robustness.

While the ARTISTIC 2.0 system was able to estimate stride length, it was done at the end of a test walk. The next step in the evolution of the system would be the implementation of real-time processing and feedback of stride length. While working with the various feedback modes it was found that the timing was critical, and could be affected by slow functions, or functions that require a significant amount of processing power. The overall program structure would need to be altered to allow correct timing and also to process the IMU data. Once it is established that the real time stride length feedback is running, the more intensive algorithms such as the state estimation algorithms and three dimensional position tracking could be added, allowing for further reduction in error and to introduce the possibilities of use on non-level surfaces.