Final Report
Wearable Vibrotactile Device
Team 25
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Executive Summary

The Sienko Research Group is looking for a reconfigurable vibrotactile feedback device to assist with research and future treatments of individuals who have gait disorders. These disorders affect the walking patterns of the individuals who have them, and can lead to falls or even mental illness like anxiety due to fear of falling. The first goal of this device is to provide feedback to participants with these disorders to help them walk more ideally, improving their lifestyles and helping them get back to a normal life. The second goal of the device is to further the research surrounding human gait, especially around implicit feedback, a newer field of research that can allow participants to have more sustainable improvements as they make their own realizations toward what is wrong with their gait and how to improve it.

This report details the design process that our team went through to create a final prototype of our design to be handed off to the Sienko Research Group at the end of the semester. This includes research into devices on the market, background information into gait disorders, as well as a formal stakeholder analysis. Requirements and specifications were then developed to give the group guidance into what the team would need to design for as the semester progressed.

Next, the formal concept development strategies that the team used were detailed, like TRIZ and functional decomposition. This lead the team to create an alpha final design, with detailed design sketches and drawings to show the initial concept. Engineering analysis was then performed on the design, like component selection, to pick out the different components that the design must use in order to be successful. This was done as a first check of the specifications for IMUs, tactors, and the logic center that the device must use.

Details regarding the software development process for the device are included to show the progression of the design and also show why different methods were ruled out by the team as the semester went on in regards to their ability to connect as a system and our teams own prior knowledge in getting the device to work. This was done to give the stakeholders an understanding of the team's extensive process used to completely determine the best way to give the researcher a code and UI to control the device. The team ended up settling on using MATLAB.

The final prototype that has been given is able to provide explicit feedback to the person wearing the device based on the IMUs attached to the person wearing the device. This feedback can be changed through the MATLAB code provided to change feedback parameters, like vibration intensity or input thresholds. The device has been verified to give real time feedback as well as fit a variety of potential research participants.

There is further validation testing that will need to be done, like the researchers using the device in a setting where the participant wearing the device has a gait disorder, in order to completely validate our design. Further validation tests, as well as the final verification steps needed, are detailed in this report to give the full scope of where the design sits at the handoff point to our stakeholders.

Overall, this report details the background, design process, as well as successes and failures of our team throughout the ME450 semester. Our team believes that we achieved a successful if not complete design that the Sienko Research Group can continue to build and use in the lab setting. It is our belief that the device, in its current state, can be used to provide explicit feedback, and then with more work and expansion, implicit feedback will be possible at the same time.

Project Introduction

Gait disorders affect many people in the world today. One way to learn more about these disorders has been to conduct testing to see if different types of feedback can help correct balance issues or prevent falling during a gait cycle. Currently, the most helpful form of feedback appears to be vibrotactile feedback where vibrating motors attached to a participant's body give feedback based on data from sensors also attached to the participant's body. However, the question remains open to what locations on the body and what type of vibrotactile feedback can produce the best results. Most devices, like those used by project sponsor Sienko Research Group, have only been able to use systems that provide explicit feedback to the participant. However, to further advance the understanding of feedback on gait, researchers want a device that can also provide implicit feedback. Therefore, it is our task to create a reconfigurable vibrotactile device that can provide both these types of feedback, as well as increase the potential participant pool size through being usable by participants of different sizes and backgrounds, while recording the information about a participant’s gait during the study.

To further break this problem description down, there are two key factors that will need to be considered. Reconfigurability in the scope of this project means numerous things. The first is the fact that the device must be able to be worn by a pool of participants that can fall anywhere on a large spectrum of body sizes, standard for adults. The device must also be reconfigurable for the researcher in terms of how the participant will receive their feedback. Vibrotactile feedback is what is preferred, but the device must have several locations in which this feedback can be given, as well as the modality of implicit vs explicit feedback be possible.

The device must also record data while the participant is wearing it during research. Therefore, ensuring that the device accurately tracks and records gait is very important. This is the only way in which the researcher will be able to determine whether the vibrotactile feedback being given to the participant is effective in correcting problems with that participant’s gait.

To summarize, our group has been tasked with creating a wearable, reconfigurable vibrotactile device that will be used by the Sienko Research Group to conduct research into the gait of participants in their studies.

Background

This section details important background information on gait disorders, 2 point discrimination and explicit vs implicit feedback. These topics were researched by our team to provide us a greater understanding of the context of the problem proposed by Sienko Research Group. Research was conducted through the use of interviews with our stakeholders, consulting the University of Michigan librarian, and using databases like PubMed to find relevant information regarding studies already completed in the field. This background information and its accompanying research provides clarification on areas pertaining to the use of the device our group will be developing, and the reasons for the research that will be conducted with it. This research was done in a team matter as well to find pertinent information to help achieve specifications that met the stakeholder requirements as described later in this report.

Gait and Gait Disorders

Gait is an individual's pattern of movement. Humans have a distinct gait cycle that differentiates them from other members of the animal kingdom. Figure 1 includes an example of a human’s gait cycle.

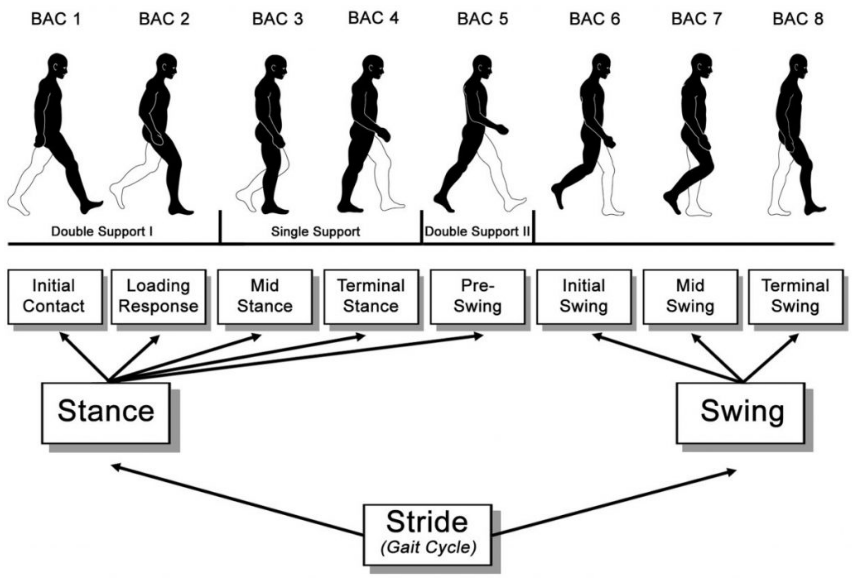


Figure 1. Gait cycle for an individual. There are eight distinct portions of the gait cycle as shown. Individuals who suffer from a gait disorder find it difficult to keep in this cycle without falling. [2]

Gait disorders are an abnormal pattern to the gait cycle shown in Figure 1. These disorders affect a wide variety of people, however of patients over the age of 80, sixty-two percent show signs of a gait disorder [3]. For these individuals, they often develop a fear of falling, and will not partake in their daily activities as they would have before developing these disorders. That is why the research being conducted around the country by groups like the Sienko Research Group is so important, as it can offer new ways to help individuals who have these problems with gait and balance.

Gait disorders can manifest themselves in different ways. These can include slowing down gait (slower walking speed), having troubles with gait initiation, or even problems with turning [4]. While advanced age can contribute to gait disorders, they also arise from numerous diseases, like Parkinson's, or even neurological disorders as a result of a stroke. One other common disorder that leads to gait issues are vestibular disorders, which the Sienko Research group has worked with in the past to try to determine how to improve these individuals' gaits. The vestibular system is in the ear, and helps the body balance by acting as a sort of gyroscope. Individuals with vestibular disorders exhibit the same tendencies as those with other gait disorders like increased anxiety associated with walking, which can also increase the rate of depression [4]. Gait with natural head movements is also more difficult for individuals who have vestibular disorders, as they have trouble moving their head naturally while walking.

Currently, there are ways to help individuals who have gait disorders. Most frequently they include clinical work through prescribed exercise that can help improve balance and stamina, thus helping improve gait [5]. Therefore, if our group can continue to advance the biofeedback rehabilitation system, through helping create a research device to be used by the Sienko Research Group, potential new forms of rehabilitation can be made for individuals with gait disorders by creating a new deeper understanding of these gait disorders and giving them a valuable device that can help them with their balance and gait issues in the moment.

Explicit vs Implicit Feedback

A fundamental part of our design problem is creating both explicit and implicit modes of vibrotactile feedback. Explicit feedback tells a participant exactly what actions to take to correct their gait pattern. For example, a buzzing or other feedback to the lower back may be used to tell the participant they are leaning too far back while walking. Implicit feedback is different in that the participant will have to make their own connections between the feedback they are receiving and the way they are walking. In the case of our project, implicit feedback will be a predetermined pattern that a researcher can set to a haptic array that represents ideal walking. The participant will then begin to walk - likely not ideally - and will receive feedback through this haptic array. The participants goal is to match what they are feeling on the haptic array to the predetermined pattern that represents ideal walking. This implicit feedback can act as a way for a participant to learn to coordinate the problems in their gait patterns without relying on explicit feedback. This is a focal point of future gait research, as there is a possibility that implicit feedback is more effective than explicit feedback in having participants retain their improvements when they leave the lab and live their daily lives without the devices.

2-Point Discrimination

2-Point discrimination is the ability for someone to distinguish two distinct points on their skin. The distance between these points can vary based on a variety of factors, most prominently the location on the body [6]. For the purpose of vibrotactile feedback, the location that has the best 2-point discrimination value is the torso [7], and has been the primary area of focus for previous commercial and research based products dealing with gait training. The 2-point discrimination test is also a very common test when trying to diagnos individuals with neurological disorders on the skin, as common values for different parts of the body are known for healthy individuals. Figure 2 shows an example of a 2-point discrimination test common in a clinicians office when testing for neurological disorders.

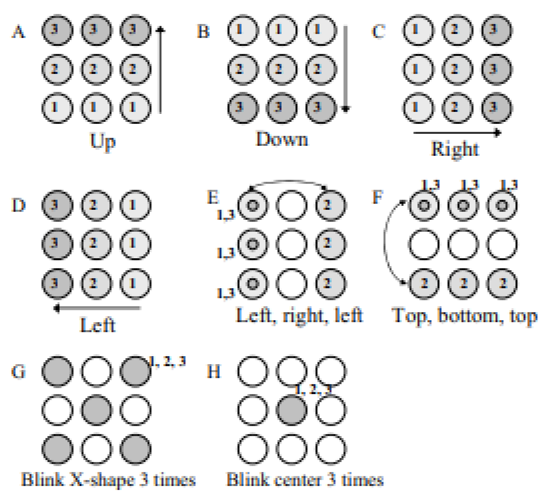


Figure 2. Implicit feedback response patterns used in previous research to determine best location for pattern recognition on the body [7]. The device used contained a 3x3 haptic display that would create different patterns on the arm and torso. This was used to determine the location on the body that best could differentiate between the different patterns A-H.

The tests like those shown in Figure 2 help determine the 2-point discrimination values of different locations on the body, like the torso and arm, as well as help distinguish which part of the body is best suited to distinguish the patterns.

Previous Work of Sienko Research Group

To more effectively discuss the work that has been done by the Sienko Research Group, a breakdown is in order. In a 2013 report, the group developed and used a vibrotactile display to relay two distinct patterns to a participant while walking [1]. All participants had been diagnosed with vestibular disorders. Figure 3 shows the device that was used in the research.

Figure 3. Vibrotactile feedback device [1] used by the Sienko Research Group in a 2013 report to look at the effect of vibrotactile feedback on postural sway. This device has a haptic display and is attached to the torso like a belt and has two battery packs.

As shown in Figure 3, devices have previously been used to determine what types of patterns are most helpful in improving the gait of a participant with a vestibular disorder. After completion, participants in this study had expressed preference for continuous feedback during the tasks assigned [1]. However, the device itself was only able to provide explicit feedback to the subject, and did not have a mode to communicate feedback implicitly to correct participant gait.

In 2017, another system was designed and used to provide explicit feedback at eight locations on the body [8]. This device was constructed as a way to address the gap between devices that monitor gait and devices that help with rehabilitation of gait. Currently, this gap exists as most devices are designed to monitor the movement but do not actually help with training an individual to improve their gait. Figure 4 contains images relating to this report.

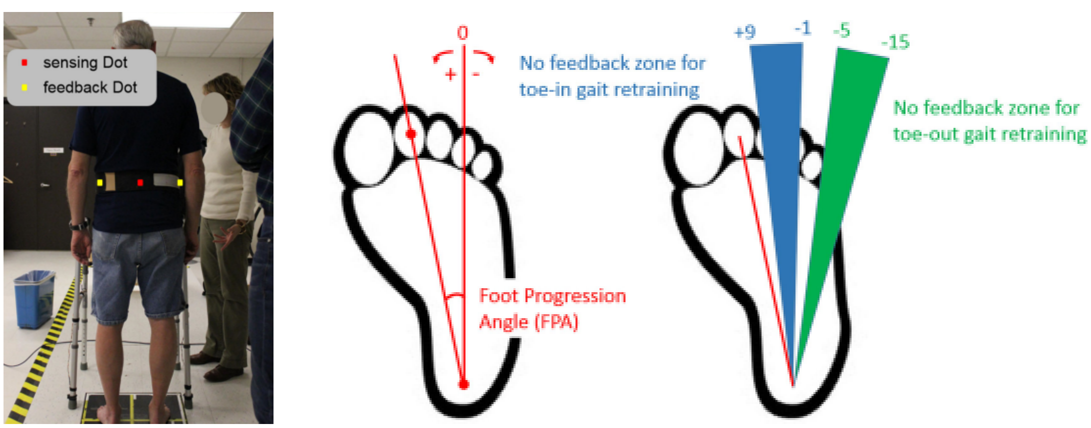


Figure 4. Proof of concept explicit feedback vibrotactile device used to improve gait. Participants wore a belt that had wireless nodes that could either track movement or give feedback based on researcher configuration and were all connected wirelessly to a central hub [8].

It was concluded that this system was able to meet its design goals of being portable, able to improve participant gait, while measuring all human movements. In the context of our design problem, while this device may serve as a bridge to a final solution, it does not have a form of implicit feedback that can be used to either help a researcher learn more about gait, or improve and train the gait of a participant.

Benchmarking Analysis

To better understand how to approach work on our design problem, we evaluated aspects of several research-based devices and one commercially available device that generally attempt to address gait problems in different types of patients. We considered several benchmarking requirements involving device feedback, cost estimates, and data acquisition for each design. A detailed description of each device is located in Appendix B.

In general, devices used in gait training and analysis involve collecting data on linear and rotational kinematics through the use of IMUs at specific points on the body (often torso, head, or foot) or collecting data on pressure at the foot through embedded sensors at multiple points on the foot. Feedback is then delivered by the device to the user based on sensor inputs. Depending on the type of feedback given by the device, user's are then expected to respond in a way that corrects their actions. These responses are often specified by researchers or experts and are meant to adjust the user's behavior during their gait cycles.

For our design problem, it is important to consider the type of feedback delivered by the device to the user. Explicit feedback is the typical choice in most, if not all, of the previous devices used in both commercial and research settings. Being explicit with the user about how they should respond to stimuli from the device they use is the simplest way for a feedback system to operate. However, this comes with the challenge of creating a "correct" response for the user to follow that may not necessarily allow the user to correct their gait patterns in a way that best fits their body conditions (accounting for sensory deprivation, effects of physical trauma, etc.). Most, if not all, existing gait training and analysis devices are based on a form of explicit biofeedback with no evidence of any successful implementations of implicit biofeedback.

The type of feedback delivered by each device is also an important factor to consider as a person may respond differently to different types of feedback. The most common means of feedback among commercial-use and research-based devices is vibrotactile feedback. Generally, vibrational motors are located at specific locations on the body, most commonly on the user's torso, and are active in response to the exceeding of predetermined threshold values by sensor inputs for parameters such as sway angle and foot pressure. Using vibrotactile feedback over other forms of feedback, such as auditory feedback, allows a larger range of patients to use a particular feedback device. Many patients with gait-related disorders have sensory impairments due to a variety of conditions that make it difficult for them to comfortably or properly balance and walk. This means that the devices need to provide feedback that can be properly received by most patients with gait-related disorders. Since many of these patients can have auditory impairments (for example, those with vestibular disorders), auditory feedback does not stand alone as the only means of feedback for any given device.

Although sensor inputs at different locations correspond to different feedback locations, the sensor locations and the feedback locations are not always the same. Some devices feature sensing in multiple locations that provide data input for feedback locations at a single location, and other devices include a secondary device for the researcher to receive feedback as well. No matter what sensing and feedback configuration any existing device includes, every device gives feedback in real-time to the participant and in some cases, to the researcher as well. It is important to understand where data is being collected as more data often yields a more complete analysis of any user's motion, and understanding where feedback is given is important for optimizing the effectiveness of any feedback to the user. Having real-time or live results is also very important for the researcher to understand the behavior of the data with respect to the user of the device as well as for the researcher to properly verify a correct calibration and to troubleshoot the device if the device does not function as intended.

Outside of the direct functions of any device, all of the existing feedback devices are wirelessly connected to a main operating device (often either a phone or computer). It is difficult to provide an effective gait training or gait analysis device if the motion of the user is limited by wiring. Wired connections between the user and the main operating device can also threaten the integrity of the equipment and the safety of the user if any person were to trip on the wiring or if the wiring were to be snagged by anything in the surrounding environment.

Having a wireless connection makes things simpler for both the user and the researcher and also affects the cost of the equipment needed for any feedback device. The overall cost of any given device can be a large block for any research or commercial application. If any existing devices had all of the necessary functions for a particular use case, a price outside of the allowed budget can prevent those devices from being purchased. Since many of the existing gait training and analysis devices are research-based, the apparent costs of those devices are low. This does not indicate that all, or even most, of research-based devices have a low cost because of their low apparent costs since no actual cost is usually given in any reports. The devices that are commercially available, often have a large associated cost due to their low demand in a rather niche market.

The following two tables (Tables 1 and 2) include information for each of the devices that our team studied in benchmarking with respect to our benchmarking requirements:

Table 1. Benchmarking requirements.

	Explicit Feedback to participant	Implicit Feedback to participant	Feedback Type	Participant Feedback location
Vertiguard [9]	✓	✗	Vibrotactile	Torso
SwayStar/Balance Freedom [10]	✓	✗	Audio, Vibrotactile	Head
SJTU Research [11]	✓	✗	Vibrotactile	Hand, Arm
Sole Sound [12]	✓	✗	Audio, Vibrotactile	Foot
Empathy-based Haptic Feedback [13]	✓	✗	Vibrotactile (Linked)	Torso
Sienko et al. [1]	✓	✗	Vibrotactile	Torso

Yasuda et al. [14]	✓	✗	Vibrotactile (Linked)	Torso
Xia et al. [15]	✓	✗	Vibrotactile	Foot
WERAHAP-PD [16]	✓	✗	Vibrotactile	Foot

Table 2. Benchmarking Requirements continued.

	Participant Sensing Location	Real-Time Feedback	Wireless	Cost
Vertiguard [9]	Torso	✓	✓	Low Cost
SwayStar/Balance Freedom [10]	Head, Torso	✓	✓	High Cost
SJTU Research [11]	Hand, Arm, Foot	✓	✓	Low Cost
Sole Sound [12]	Foot	✓	✓	Low Cost
Empathy-based haptic feedback [13]	Foot	✓	✓	Low Cost
Sienko et al. [1]	Torso	✓	✓	Low Cost
Yasuda et al. [14]	Foot	✓	✓	Low Cost
Xia et al. [15]	Foot	✓	✓	Low Cost
WERAHAP-PD [16]	Vicon Motion Capture System	✓	✓	Low Cost

It is apparent from our benchmarking analysis that none of the existing feedback devices intended for gait training and gait analysis meet all of our benchmarking requirements. All of the devices give a form of explicit vibrotactile feedback in real-time, but do not offer any form of implicit vibrotactile feedback. Since both forms of feedback are required (see requirements and specifications section) by our stakeholders, this is the most apparent block for choosing any of the benchmarked devices. It is also important to note that our desired sensing and feedback locations (see requirements and specifications section) include the head, torso, arm, and feet which are not all included by any existing devices. Both the lack of implicit feedback and the lack of sensing and feedback in all of the desired locations on the body eliminate all existing devices as solutions to our design problem since all other benchmarking requirements are satisfactorily met (explicit, real-time, vibrotactile feedback provided by a low cost device that is wirelessly connected to a main operating device). Therefore, these failures to meet our benchmarking requirements justify the creation of a new solution for our current design problem.

Stakeholder Analysis

Constant communication with stakeholders is an essential part of any design process. To ensure that our group had meaningful meetings with our stakeholders, we developed a plan early on to engage in a manner that made sure not only ourselves, but the stakeholders would receive what they were looking for every meeting.

To start, our group has kept a running document to log any information obtained from meetings as well as writing questions beforehand to ensure that we would always have useful communication. Early on in the design process, our first meeting was used as a way to complete some basic stakeholder analysis. Figure 5 is a visual representation of this analysis.

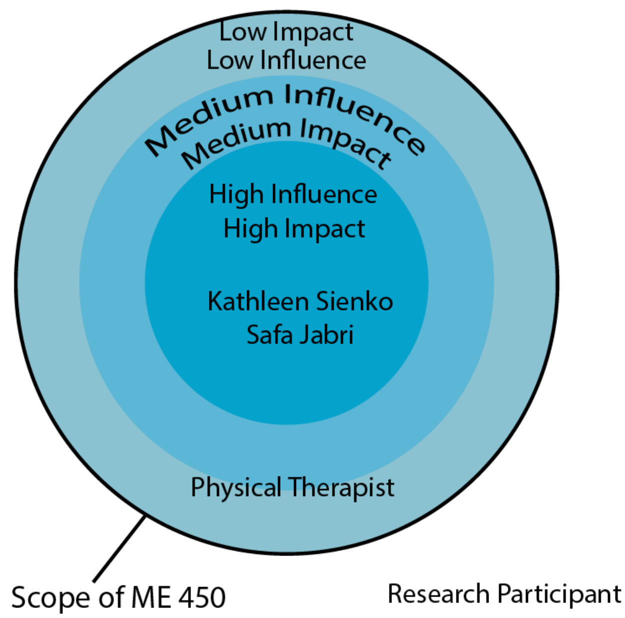


Figure 5. A visual representation of our stakeholder matrix. Our main stakeholders, Dr. Kathleen Sienko and graduate student Safa Jabri, are placed in the high influence high-impact portion of the diagram. A future physical therapist was identified as someone who would have low influence and medium to low impact. Finally, a research participant is identified as an individual who will be affected, but sits outside the scope of the ME450 project.

To further explain each stakeholder, both Dr. Sienko and Safa Jabri are the point of contact for our group to develop this project. To the end of the first design review, our group has met twice weekly with doctor Sienko and conducted three Zoom video meetings with Safa. On top of these, our group has had email communications to further clarify any areas where confusion arose. This communication included sharing requirements as our team developed them as well as sharing updates on what research we had come across early on in the process to ensure our team had a complete understanding of the laboratory work.

In the future it is our group's hope to talk with a physical therapist on the University of Michigan campus to further gain an understanding of the implications of this device and gain more insight into how the research conducted could affect future physical therapy techniques. Also, participant comfort is something that a physical therapist can comment on and meet the timeline and scope of the ME450 project.

Design Process

The design process the group chooses is very important because the design process we end up deciding on is how the flow of our project will follow. The largest consideration the group had for choosing a proper design process is having room for iteration. This project has an intersection of many fields and skills that require us to learn a lot as we go. This is why iteration is important for every design process to better improve the design but in our case, the amount of knowledge we are all gathering each week means our understanding and choices are going to have rapid changes. The fast learning and changing nature of our project mean having a clear way to iterate designs will be important especially when building the prototype.

The next area the group found very important was a large problem definition phase. The research area of gait and the vestibular system has many working pieces to it that can affect the way we use sensors to capture one's gait pattern and the way we want to deliver feedback. This will mean as we move forward through the design, further research and problem defining will keep coming back into the picture to make more informed decisions. Another aspect along with having more time for research and more room for iteration is having a larger time spent in the prototype phase. This is essential for fine tweaking the final design because in order for a prototype to be deemed successful in our case it must be physically tested. This is why it is essential to our project to maximize the time spent in prototyping along with using iteration to refine our design to work as intended.

After identifying key aspects the group wants to capture in a design process, the next step was to view different processes that work well. The main two branches observed for design processes are solution-oriented processes and problem-oriented processes. The solution method is more focused on generating a solution then analyzing and modifying it until a final solution works. This method seemed to not fit our project very well since the solution for our problem is not very simple. The solution method can work for less complex solutions because it can be much more time efficient to jump to a solution and quickly test and make adjustments. A problem oriented process works better for our project as it will allow for more diverse concept generation and solution neutral requirements and specifications. Figure 6 shows the design process that our group has decided to use over the course of the semester.

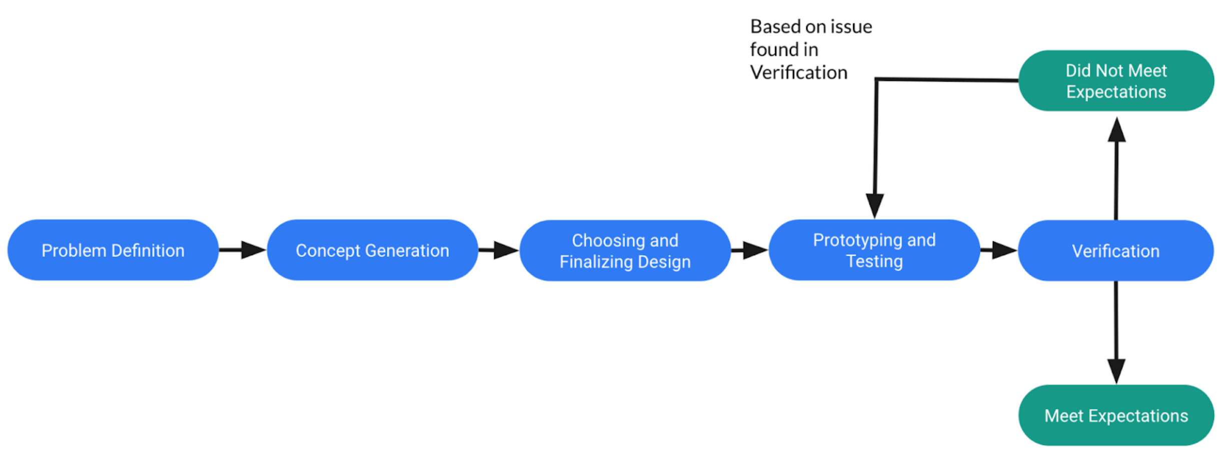


Figure 6.

Contextual Factors

Social, Global, and Cultural Impacts:
There are many different impacts seen by different perspectives of the project. From a social perspective, many people lose out on their ability to maintain active and fulfilling lifestyles, our device could allow these people to get back to regular life. The global implications could be a jump start of new ideas and more research projects that arise from our research of gait and especially our research into the newer field of implicit feedback. Culturally this device seeks to help participants from a wide range of backgrounds from all around the world. It is important that our device is inclusive and can be used for people from all over the world regardless of attire, body size, shape, gender, or any number of differentiating factors. For example, if our device is inclusive, it should be wearable for all the different religious clothes people around the world may wear.

Environmental Impacts and Sustainability:
Our wearable feedback device for gait research addresses an important social challenge: people with balancing disorders all over the world struggle to maintain active and fulfilling lifestyles because of their inability to walk effectively. Should our device be successful, it has large positive implications for millions around the world. The current scope of the project is to create a single device that could directly help a few people, but the knowledge learned from the device could be useful for other researchers and physical therapists around the world. Although our device uses finite resources like batteries and other non-sustainable materials, the limited production of the device means that the device won't drain the Earth's natural resources. Finally, as long as the device can be produced with the research budget available, it is economically feasible. Because the device meets the needs of society, the environment, and the economy, it is a sustainable technology.

Ethical Issues:
It is our responsibility as engineers who are designing a wearable device that the safety of the participant is the first priority. This means upholding all the safety standards set for an electrical device are satisfied. Additionally, any sort of concerns the team faces with ethics should be consulted with stakeholders. Because our device will deal with people who have gait or balance disorders, it's important that our device does not worsen the gait of these individuals or present additional risk toward falling. If there's even a slight possibility that our device could worsen these disabilities, it would be unethical to continue our work before resolving these problems.

Positively and Negatively Affected Stakeholders:
The stakeholders identified in the scope of our project will all be positively impacted if the project can be executed successfully. The Sienko Research Group can have the potential to get more funding and new projects to further the work with gait. The PhD student we work with will be positively impacted by the continued work toward her area of interest. Physical therapists and other medical professionals will be benefited by a successful device as they can better care for those with gait disabilities. The only groups identified that may be negatively impacted are other research groups and companies in the market that could be pushed out of the market by our success.

Power Dynamics in our Design Project:
Our team has power over our stakeholders as we control the design process and the design decisions. This is a form of visible power in our project. Our key stakeholder - Dr. Sienko - has power over our project because she controls the funding and availability of other resources to our team. This is a type of visible power she has over the group. Dr. Sienko also has an invisible or hidden power over the team because she is an expert in the field of gait research. She has the ability to influence team decisions

based on her past experience, expertise in the field, and hold over the resources that are needed to complete the project.

Requirements and Specifications

A list of requirements and engineering specifications were created to address the two design problems our team is working on. The first list of requirements and specifications addresses the wearable feedback device that a participant will put on to receive some feedback - most likely vibrotactile - from data collected by sensors mounted on the participant. The second set of requirements and specifications deals with the interface that researchers and physical therapists can use to configure the wearable feedback device.

Listed below are the requirements and specifications for the wearable feedback device. Our team worked to continuously improve this set of requirements and specifications as our understanding of the problem increased over the course of the semester. The specifications listed below are our final, finished list of requirements and specifications.

Priority	Requirement	Specifications	Sources
High	Reconfigurable Wearable Device	1. The device must accommodate a head circumference of 50-62.7cm 2. The device must accommodate a wrist circumference of 12.7-20.4cm 3. The device must accommodate an ankle circumference of 15.9-26.7cm 4. The device must accommodate a waist depth of 13-29.9cm	1. Military Anthropometry Database [17]
High	Comfortable for Subject/Does Not Affect Gait	1. Participant worn devices < 5.5 kg 2. Devices on extremities < 1.5 kg 3. Device has no common allergens - Formaldehyde resins that can cause rashes on participants 4. Wires secured to the body without adhesives on skin 5. Wires < 2 cm from body 6. Device can be put on participant in < 2 mins	1. C. Phonpichit et al [18] 2. J.D. Rose et al [19] 3. Wunpen et al [19]
High	Wireless Connection to User Interface	1. Range of 0-(-60dbm) indicating good signal strength 2. Range of 13 meters from the computer or phone operating the sensors 3. 1000 mAh battery to power the device for about 1 hour of use	1.Bluetooth.USB.3. Guide [20] 2. Bluetooth.USB.3. Guide [20] 3. Power Consumption Sources [21]
High	Explicit Vibrotactile Feedback	1. Haptic feedback in sensory range of participants (vibrating motors capable of 60 to 300 Hz) 2. Feedback to head, left arm, torso,	1. Goncalves et al. - 2018 [22] 2. Interview 1 [23] Suliman et al. - 2021 [24]

		and both legs	
High	Implicit Vibrotactile Feedback	1. Haptic array of 3x3 to 5x5 feedback points 2. Minimum 60 mm between feedback pointsfor two point discrimination 3. Haptic feedback in sensory range of participants (vibrating motors capable of 60 to 300 Hz)	1. Jouybari et al - 2021 [25]
High	Sensors capture body kinematics	1. Velocities up to 10 m/s 2. Accelerations up to 70 m/s^2 3. Angular velocities up to 500 degrees/s 4. Angular accelerations up to 10000 $degrees/s^2$ 5. 60-120hz sensor sampling rate 6. At least: 1 sensor on head, 1 sensor on left arm, 1 sensor on torso, 1 sensor on each leg	1. Interview 2 [26] 2. Suliman et al. - 2021 [24] 3. Richards et al - Biomechanics ch 15 [27]
High	Electrical System is Safe for Participants	1. Patient leakage current does not exceed 100 μA 2. Ground current does not exceed 500 mA	1. IEC 60601-1 [28] 2. IEC 60601-2 [29] 3. IEC 62366-1 [30]
Medium	Lasting	1. Wire connections are soldered and wire connector clips are used to attach and detach tactors 2. The sensor attachment harness can be washed without damage	1. Interview 3 [31]

Creating the wearable feedback device is the more important of the two design problems and many of the requirements for this device are high priority. Some of the most important requirements and specifications of the device are explained in paragraphs below.

Reconfigurable Wearable Device:
It's important that the wearable device can fit a variety of participants. We used a military anthropometric database to establish bounds based on a 5th percentile female to a 95th percentile male. If the device isn't inclusive toward all genders and body sizes, we may have accidental bias in our research. For example, if our device only fit people of small proportions, and it was true that larger bodied males had a more difficult time balancing, our device might not capture that important trend and limit the strength of our conclusions about gait disorders.

Comfortable for Subject/Does Not Affect Gait and *Wireless Connection to User Interface:*
These next two requirements address different needs of the device, but are both targeted toward making sure the participant's gait remains unaffected during testing. Keeping the weight of the device low, tightly securing wires to the participant's body, making the harness out of hypoallergenic materials, and having no wires between the device and researcher interface all ensure the most comfortable and natural gait possible for the participant so feedback given during tests with the device can translate into real world

improvements without the device. In order for the device to be wireless, a battery is necessary to power the sensors and motors used. A rough calculation was used to determine the battery capacity by finding the amount of power usually drawn from sensors, motors, and a logic controller to come up with the capacity needed for an hour of use.

Explicit/Implicit Vibrotactile Feedback:
We want our wearable device to be able to provide explicit feedback to different parts of the body that are underperforming as well as implicit feedback that allows the participants to make improvements without directly telling them what they need to do to improve their gait. Explicit feedback should be given to the head, left arm, torso, and both legs. Stakeholder experience [26] suggests that these feedback locations are the most important for signaling a participant what to change to improve their standing balance and gait. Implicit feedback is a more open ended problem. The most important specification of implicit feedback is that there needs to be some sort of haptic array that researchers can encode patterns into. A 60 mm separation between haptic feedback locations comes from the two point discrimination of a human torso.

Sensors Capture Body Kinematics:
Sensors should be placed all over the body to capture the kinematics of the head, arms, torso, and legs. These sensors must have a high enough sampling rate to fully capture the kinematics of a human, and the sensors must be able to capture the sometimes high accelerations and velocities that different limbs of the body experience at points in the gait cycle.

Safe for Participants:
Our last high priority requirement is that our device is safe for participants. While verifying our device for use on participants outside the Sienko Research Group and our own lab group is outside the scope of ME 450, making sure our device is safe according to existing standards is still important. IEC 60601 and 62366 give some requirements of a device that includes electrical components.

Lasting:
A medium priority requirement, our device should be washable between participants and all components of the device should be secured so as to not fall apart when being transported. This means that loose breadboarded connections will not be appropriate and that all sensors must be securely fastened to only capture the kinematics of the participant's body, and not the shaking of the device.

Listed below are a second set of requirements and specifications for the researcher interface that will help use and control the wearable device.

Priority	Requirement	Specifications	Sources
Medium	Configurable User Interface	1. Ability for researcher to define rules to create control signals for feedback 2. Input vibrating feedback intensity, pattern, and sensor thresholds for vibration in < 2 mins / (2 minutes maximum downtime between participant trials) 3. Input subject ID, age, weight,	1. Interview 3 [31]

		disorder, trial number, date and time < 5 mins / (5 minutes maximum setup time for each participant) 4. Ability to export data into csv format	
Medium	Functional Software Language	1. MATLAB, Python, C software 2. Can stream data to the user software for troubleshooting/ calibration of device	1. Interview 3 [31] 2. Interview 4 - Safa [32]
Low	Portable	1. Researcher device weighs < 2.5 kg 2. Researcher device is wireless from wearable device	1. Interview 4 - Safa [32]

Configurable User Interface:
A configurable user interface should allow researchers and physical therapists to easily interact with the participant during trials. The user should be able to define rules for feedback based on sensor input, configure the device quickly (<2 mins), set up tests for a new participant quickly (<5 mins), and export data easily.

Functional Software Language:
Our stakeholders are experienced with MATLAB, Python, and C so we aim to develop our user interface in one of these languages. Our stakeholders also wish to have the ability to livestream sensor data to the user interface for troubleshooting and device calibration. Neither of these specifications are quantifiable, but due to the nature of the requirement it was hard to assign numbers and units to the different design specs. Instead, these specifications will be tested by the user once a prototype is made.

Portable:
A final and low priority requirement is that the researcher interface should be portable. Because the researchers sometimes have to follow an individual if they have especially bad balance issues, it is more convenient if the researcher interface is handheld.

Discussion of Requirements:

Wishes vs Needs:
Our feedback device must be able to accommodate a large variety of participants and give explicit and implicit feedback based on captured body kinematics. The device must be safe and must not affect the gait of the user. We want our device to be lasting and made of comfortable materials, but it is not necessary that these two requirements are met to fulfill the goal of the project. Additionally, most of the requirements for the user interface device are more “want” based instead of “need” based. Researchers will have an easier time interacting with the participants if the user interface of the researcher device is streamlined and uses a simple software language like MATLAB. It will also be easier for the researchers to work if the device is hand-held rather than bulky. However, these requirements are wishes of our stakeholders and are not as critical as designing a functional wearable device.

Quantifying Specifications:
While most engineering specifications have been quantified to provide specific numerical goals that the team can work toward, there are a few specifications that have not been quantified. We recognize that

some specifications may need changes as we learn more and iterate on our design. However, the team believes that almost every specification is at least testable and can be verified by a prototype. The exceptions are some of the specifications under the requirement “Electrical System is Safe for Participants” which come from standards that give qualitative suggestions on how to best contain electrical systems. We believe that electrical safety is an important requirement, but we have yet to find a source of information that quantifies these qualitative specifications. Finally, the specification that we have a written set of instructions for how to use the device was a stakeholder recommendation that the team believes is valuable, but again has not been able to quantify. As we continue our design process it may become apparent that this specification is not needed, or that as we prototype, a set of instructions or a “manual” of some sort becomes a valuable part of the project.

General Discussion:
All requirements and specifications were determined by stakeholder engagement and existing literature. Requirements and specifications were shared with our key stakeholders during our presentation on Feb 8th 2022. Our requirements are listed in order of importance. The importance of the requirements was determined by stakeholder engagement and our table reflects that communication between our stakeholders and the team. Besides the acknowledged specifications that still need some work, we believe that our specifications necessarily fulfill the requirements and that our list of requirements is complete and necessarily solves the design problem if all requirements are met. The listed specifications are all reasonable and within the scope of ME 450, meaning that we can test to make sure all specifications are met during this semester.

Future Challenges and Planned Actions

There are many different challenges that pose a threat to the success of our project. The goal of this section is to outline the problem seen and have a plan to address these challenges foreseen.

Software

The task of designing a reconfigurable interface with software that can be manipulated is a difficult task. This is because there is not a lot of expertise from the team members in developing software. That being said the group has experience working with Matlab in basic controls and data analysis applications. This experience can give us some base knowledge necessary but that alone will not be enough to make sure we are successful for this project. The group is planning to do more research online to see effective ways to have data from sensors sent in real time to a computer or phone in other contexts outside of the biomechanical scope. This along with being able to order sensors and motors sooner in the design process will allow for more time practicing and developing code and getting feedback from Safa and Professor Sienko on how the design meets expectations.

Reliable Data

One of the most important aspects to the project that can be overlooked is the actual data that is being collected and used. It is easy to focus on all of the deliverables with the device and the software the researcher will interface with but if the actual data being collected is unreliable, a lot of the work performed will be of no use. This is why it is important to interface and potentially build simple prototypes showcasing whether or not the sensors are providing valuable information. The plan is to connect an individual sensor at all of the locations one at a time and do a rotation and walking test seeing what data is being collected and discuss with Safa how each of the individual locations are looking.

Sourcing Components

The issue that COVID has especially placed on many teams and companies is the supply chain shortages. Many different components and parts are taking much longer to receive or not being made at all. This is why it is crucial as a team to come to some sort of agreement on critical components as soon as possible and see what the process and time is to get the parts and if issues come up making decisive decisions to move forward with more accessible parts.

Wiring

The wiring setup for how the sensors and vibrotactile system connect to the power source are crucial for delivering a wireless experience. The whole reason behind this is to not restrict motion which can alter one's walk. The wiring setup to the power source has the potential to restrict motion which is why it is important when mounting the wires to the participant there is no restriction of mobility. This will require us to think ahead when designing and make iterations when the device is ready to be mounted to ensure this.

Implicit Feedback

Implicit feedback is an area where the solution is not the most clear. The way to deliver implicit feedback that is meaningful to the user has not been proven in a clear way which is why the Sienko Research Group is searching for a solution. At this point in the project it is important we work with Safa and Professor Sienko to make sure the hardware we decide to go with has room for future implicit implementations. The group will work closely with the stakeholders to work through this challenge together and potentially bring new ideas to the table.

Conclusions from Start of Design Process

The work that has been done throughout the early design process has laid a foundation for the problem and all the different factors associated with gait. This includes why people have issues with gait, where current research lacks, and benchmarking various products to understand what has been done before. The gaps in the market have been proven and show where we can be successful by creating a device that can track and give feedback at the different locations across the body which was not found from benchmarking. This also is where we found that implicit feedback has not been proved to work in an impactful way. This led us into developing our requirements and specifications that were shaped by stakeholder meetings to better understand the scope of the project and finding reliable sources to back up the specifications needed to deliver on the requirements outlined.

The project challenges have also been outlined to talk through why the team views them as challenges and actions planned to be taken to overcome these. These actions may be specific to theorized problems, but in the future to address unforeseen issues our group plans to take a measured approach at first solving an issue internally before going to external sources. The project schedule has accounted for some of these challenges up until Design Report 2 to the best of our knowledge. Furthermore, our plan is to continue to engage stakeholders on a weekly basis to ensure that significant progress is being made towards our end goal of developing and delivering a device that can advance the research field while also trying to provide a solution to train gait.

While we have learned a lot of gait and the shortcomings and successes of previous devices, it is important for us to make sure that the steps taken are documented to provide reference and help to future groups that also work within this field. At this point, we fully expect to deliver a product that will meet our design problem goals. Significant progress has been made to frame our design process moving forward, and it is our belief that this is the primary outcome at this point. We will continue next with concept generation and selection and report our findings.

Contextual Factors Breakdown

Any engineering design team must consider numerous contextual factors when designing a product to be used by human users. In our team's case, creating a device that will be used in a more medical sense, it is very important to think of the wider factors that could affect our development. This section outlines the contextual factors that were considered when designing the vibrotactile feedback device.

Global

The main purpose of this device is to help researchers better understand what types of feedback can help participants with gait disorders have a close to normal gait cycle. If the device is successful in doing this, researchers will be able to publish the feedback modes that provided the best results and further development can be made on devices that help people with gait disorders. The biggest global contextual factor surrounding this device is how it can help people in the medical field understand and correct gait disorders in individuals.

Social

Socially, people who experience a gait disorder are more likely to be reclusive and not live their daily lives to the fullest. Creating a device that will enhance the understanding of how feedback can affect gait will only help lead to the development of a more commercialized device that everyday people can use in their own homes. If these devices became readily available, then people who experience gait disorders would be more free to live their daily lives to the fullest, and avoid the fear of falling that too often keeps them indoors and away from the experiences that make up everyday life.

Environmental

Whenever working with a device that contains many electrical components, a group must consider the end of life results for those components. That is no different from our group, as numerous electrical components and batteries are used in the construction of our device, whether they be powering the system, IMUs or tactors. Our group must consider the disposal of these electrical components, and how they could affect the surrounding environment. Furthermore, our device makes use of velcro, which uses polyester as a key component, so making sure that the plastics we use are not harmful to the surrounding environment where they are disposed of and produced is another thing to take into consideration when selecting the materials.

Cultural

The primary cultural factor that needs to be considered has to do with the device being wearable. Therefore, if someone for any reason has limitations on what they must wear due to religious, cultural or personal beliefs that they hold, our device must be able to accommodate them. If we do not consider this when creating our design, then we could potentially limit the participant pool for a researcher or put a participant in a disadvantaged spot.

Ethics

When considering the ethics surrounding our device, the primary focus revolves around transparency of how the device works and how successful it is. When using any type of technology, users often want to be made aware of any problems that could be caused by the device, how the device works, and the effectiveness of the device. To start, in the case of the vibrotactile feedback device, clear instructions will need to be made on how to equip the device to a research participant, how the feedback modes can be changed through the UI and how to attach and detach different tactors and IMUs. Doing this avoids the dilemma of the device being used in the wrong way. Furthermore, we will need to add some electrical warnings, as the device contains wiring that could become detached throughout the process if a connection were to fail. When these connections fail, the wearer could be shocked, so we will want to be sure that when we create these connections they are sturdy and strong. Finally, properly communicating that the device is to be used in a research setting, as well as its limitations, is of the utmost importance as we want to be clear and correct with the information that we are giving to our stakeholders when handing off the final device and design.

Concept Development Methodology

Having a well thought out methodology to develop a design is an important step when tackling such a large problem like we have been tasked with. The vibrotactile feedback device that we are creating has multiple subsystems that can be seen in Figure 7.

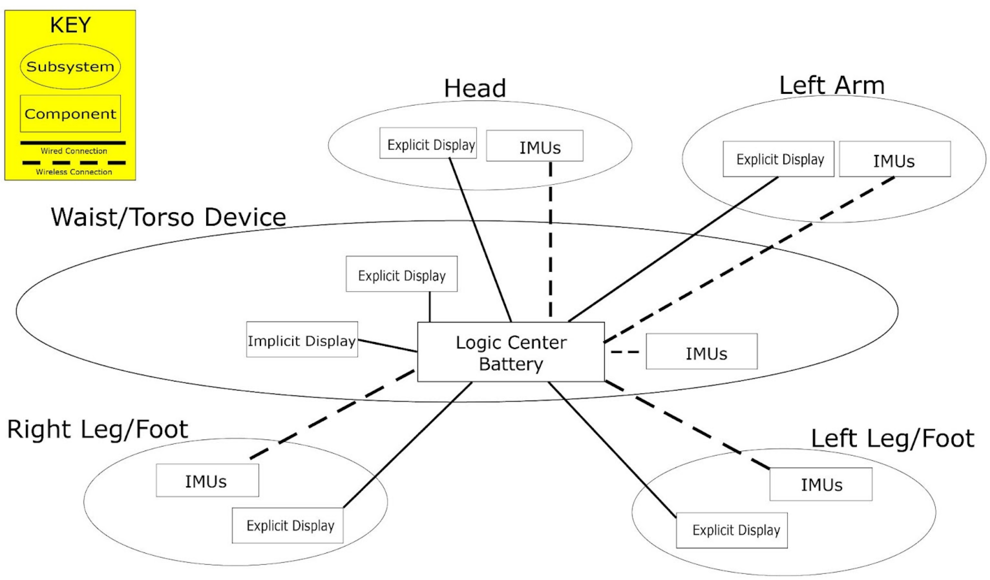


Figure 7. Subsystem map of the vibrotactile device to be developed by our group. This map serves as the foundation of our design thinking process as it outlines the subsystems that we must create to achieve a workable solution by the end of the design process.

After identifying the main subsystems of our design, we then turn to developing our methodology. This can be seen in Figure 8.

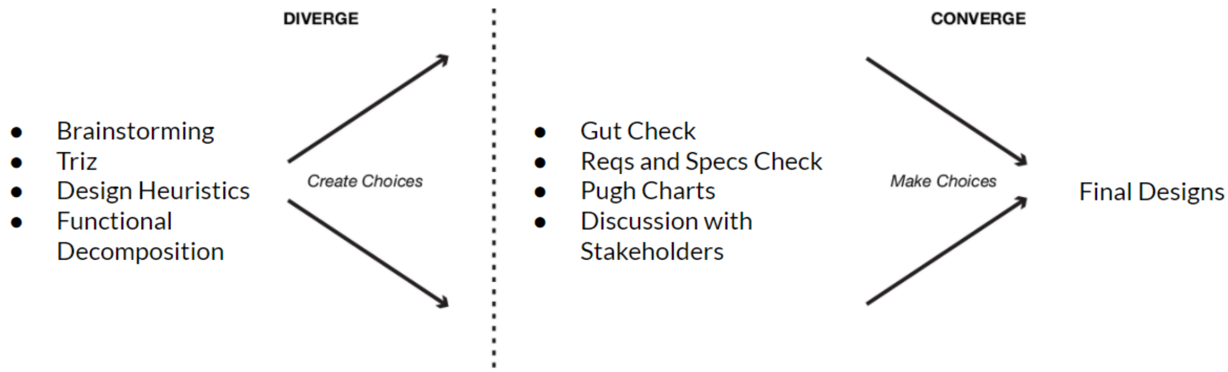


Figure 8. Diverge and Converge concept development methodology. This process involves first diverging through the concept generation strategies shown, then converging through the selection methods to get to an alpha final design solution.

This section will outline both the divergent and convergent thinking processes used, as well as showing examples of concepts that were developed through these processes.

Divergent Thinking

Divergent thinking is a necessary tool used in developing design concepts and exploring the entire solution space. Our team used four divergent thinking tools to generate concepts: Brainstorming, TRIZ, Design Heuristics, and function decomposition or morphological analysis.

Brainstorming

Brainstorming was the first concept generation method we used because brainstorming encourages out of the box solutions that might not be feasible, but can provide new perspectives for thinking about the project. The group first brainstormed separately as part of the Concept Generation Learning Block, and then we came together to combine our ideas and brainstorm as a group. Brainstorming helped our team escape the fixation of vibrotactile feedback and give other solutions for feedback to our participants more attention.

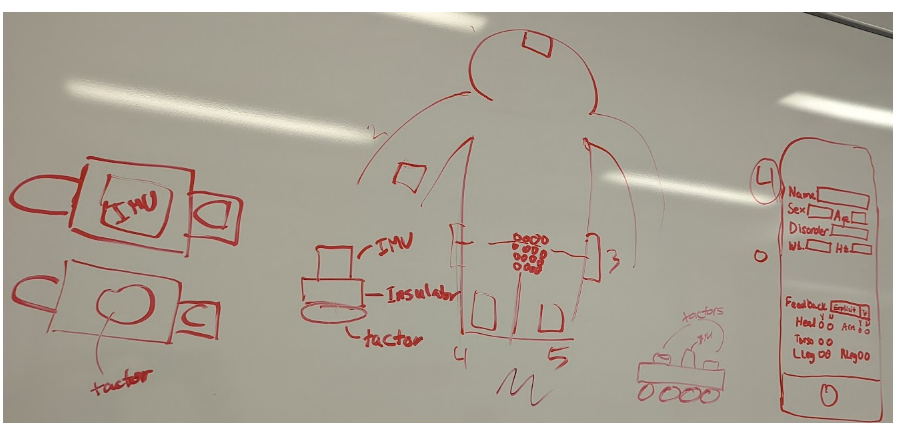


Figure 9: Rough sketch created from a brainstorming session. Shown in the image are concepts for the implicit array, designs for the tactor and sensor straps that would go onto a participants arms and legs, and an idea for a user interface that researchers or medical professionals could use to work with participants wearing the device.

Figure 9 shows one example of ideas generated from a brainstorming session. A useful idea generated in this session was the strap-mounted sensors and tactors that would receive and deliver feedback to participants. Brainstorming naturally led into other divergent thinking tools that helped us explore the solution space such as TRIZ, Design Heuristics, and function decomposition.

TRIZ

Our team used the TRIZ creativity triggers to perturb our thinking into jumping to new conclusions. We used the ideal outcome, bad solution park, and smart little people creativity triggers from TRIZ. Some of the ideas our team generated are shown below in figure 10.

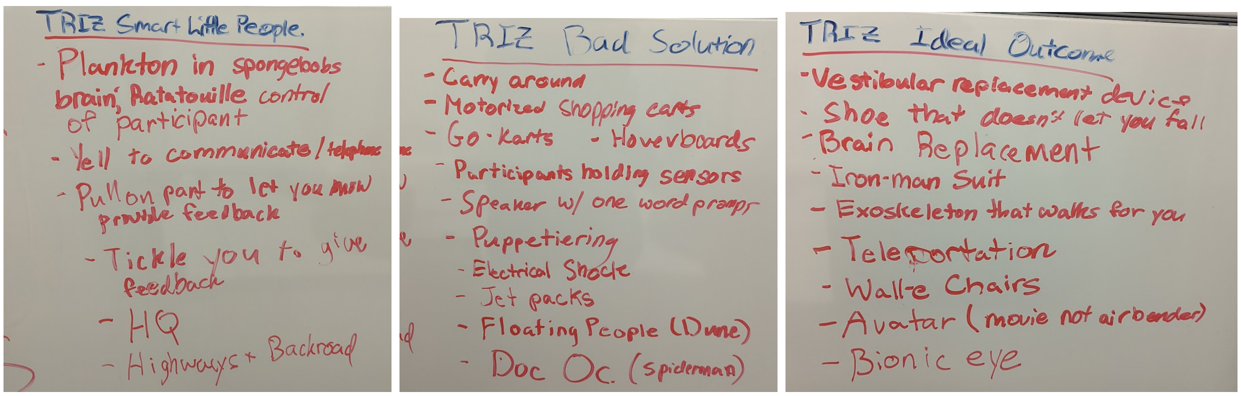


Figure 10: The idea generation above shows ideas generated from each of the three TRIZ creativity triggers that we used. The smart little people gave insight into how to communicate between our sensors, controller, and tactors. The ideal outcomes helped us think about extra functionality that our design should have to be more 'ideal', such as making sure our device improves participants' life permanently instead of temporarily.

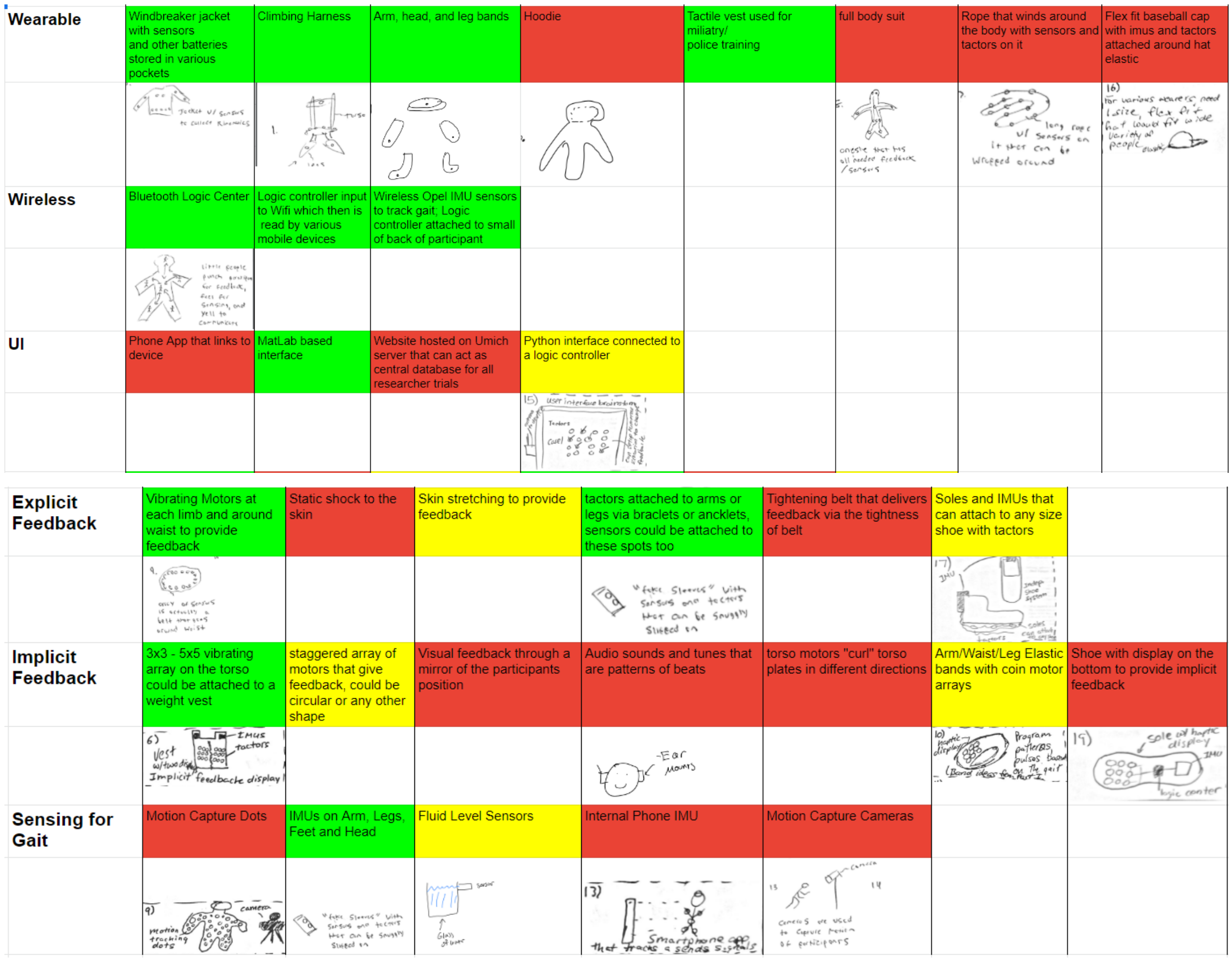
The TRIZ bad solution park didn't provide many useful solutions, but it did help us realize things we wanted to avoid, like providing temporary solutions to participants or providing solutions that work around gait disabilities without any real improvement in the participant's gait.

Design Heuristics

Design heuristics was briefly used to help our team be more creative with the design of the device. One design heuristics that reads "utilize opposite side" helped the team consider where to place the haptic feedback motors on the wearable device. Without realizing it we were limiting ourselves to only placing feedback devices on the outside of the wearable device, but after considering the card we realized that placing the feedback device on the inside of our wearable device would be more practical and more effective.

Function Decomposition/Morphological Analysis

Our team used function decomposition, or morphological analysis, to break down our design into subsystems and consider possible solutions for each subsystem. This was the most useful concept generation tool for our team and provided the avenues that would lead to a final design.



Wearable	Windbreaker jacket with sensors and other batteries stored in various pockets	Climbing Harness	Arm, head, and leg bands	Hoodie	Tactile vest used for miliatry/ police training	full body suit	Rope that winds around the body with sensors and tactors on it	Flex fit baseball cap with imus and tactors attached around hat elastic
Wireless	Bluetooth Logic Center	Logic controller input to Wifi which then is read by various mobile devices	Wireless Opel IMU sensors to track gait; Logic controller attached to small of back of participant					
UI	Phone App that links to device	MatLab based interface	Website hosted on Umich server that can act as central database for all researcher trials	Python interface connected to a logic controller				

Explicit Feedback	Vibrating Motors at each limb and around waist to provide feedback	Static shock to the skin	Skin stretching to provide feedback	tactors attached to arms or legs via braclets or anklets, sensors could be attached to these spots too	Tightening belt that delivers feedback via the tightness of belt	Soles and IMUs that can attach to any size shoe with tactors	
Implicit Feedback	3x3 - 5x5 vibrating array on the torso could be attached to a weight vest	staggered array of motors that give feedback, could be circular or any other shape	Visual feedback through a mirror of the participants position	Audio sounds and tunes that are patterns of beats	torso motors "curl" torso plates in different directions	Arm/Waist/Leg Elastic bands with coin motor arrays	Shoe with display on the bottom to provide implicit feedback
Sensing for Gait	Motion Capture Dots	IMUs on Arm, Legs, Feet and Head	Fluid Level Sensors	Internal Phone IMU	Motion Capture Cameras		

Figure 11: the image above shows the tabulated function decomposition our team used to generate concepts and start to evaluate concepts as well.

The six subsections that our team used to generate more specific concepts were wearable, wireless, UI (user interface), explicit feedback, implicit feedback, and sensing for gait. Sketches are included under some of the ideas to help describe the idea. The chart above is a good representation of the entire solution space excluding some more "out there" ideas. The color coding on the function decomposition figure represents the beginning of our converging process to narrow in on a final design and will be discussed below.

At this point of the divergent process we felt we had fully explored the solution space. Several ideas had been generated for every subsystem and we could not think of any new ideas that weren't a combination or were included in previous ideas. The next step in our concept generation process was to begin to converge on a final solution.

Convergent Thinking

Convergent thinking is the means by which our group took the many ideas we had generated and narrowed it down to just one idea we want to implement this semester and one more ideal solution that could be better suited for large scale production and use. The convergent thinking tools we used to assist our process were: gut checks, requirements and specification checks, Pugh charts, and finally a discussion with stakeholders.

Gut Checks

Our team considered whether each idea shown in the function decomposition chart in figure 11 was technologically feasible and realistic. The ideas highlighted in red in figure 11 represent ideas that did not pass the “gut check”. These ideas included elements that were beyond current technology or weren’t realistic to implement. Some of these ideas included motion capture cameras to collect data on a participant’s gait, static shocks as the feedback to the participant, and vibrotactile ropes. While all of these ideas have some benefit (motion capture cameras remove components from participant’s bodies, static shocks are easily felt, ropes are one size fits all), the ideas were not feasible due to being not accurate enough, potentially painful, and nearly impossible to implement.

Requirements and Specifications Check

The next filter our groups passed the remaining ideas through was a check to see if our remaining ideas all necessarily fulfilled all of our requirements and specifications. The ideas that passed the gut check, but failed the reqs and specs check are colored yellow in figure 11. Among these ideas were a Python based interface, skin stretching feedback, staggered implicit motor arrays, and fluid level sensors.

The use of Python was eliminated in this step because the group has almost no experience with Python, but has years of experience with MATLAB. Although Python would be a functional software language, and is both realistic and technologically feasible, the group realized that there would be no point sending Python to a Pugh chart because it would have introduced the complexity of learning a new language which could cause the project to go off schedule.

Skin stretching feedback was eliminated here because it has the potential for being uncomfortable for the participant. One of our requirements is that the device must be comfortable, and one of the specifications under that requirement is that the device should not irritate skin. People with balance disorders are often advanced in age, and with age can come other complications like frail skin and an ease to bruise. Skin stretching was removed because it has the potential to irritate the skin and therefore cause unnecessary discomfort to our participants.

Staggered motor arrays (diagonally oriented arrays) were removed because they are more complex than a simple 3x3 array and have no benefits over the 3x3 array. Part of the reqs and specs of our device is that it must be easy to reconfigure and deliver effective implicit feedback. A staggered array of motors has the potential to complicate our design and make it less effective than a more simple choice like a 3x3 array.

Fluid level sensors were an interesting idea that the group came up with in brainstorming. The idea of these sensors is to characterize the stability of a person's gait based on the motion of an enclosed fluid attached to the participant. While this idea has the potential to revolutionize how gait is characterized, it is also incredibly complex. The fluid level sensor was eliminated in this step and not in the gut check because the idea had a lot of potential, but was ultimately too complex and out of the scope of our project.

Pugh Charts

The remaining ideas, highlighted in green in figure 11, were evaluated against each other in Pugh charts to narrow in on a couple final solutions that would be discussed with stakeholders. We revisited our subsystems and revised the categories to make our comparisons, grouping the categories about feedback and dividing the wearable category into different parts of the body. The figures below show the Pugh charts that we made to evaluate our final ideas.

Vibrotactile Feedback	Weights	Wired Tactors	Wireless Tactors
Power Need	1	**0**	0
Close To Torso	2	**1**	-1
Far From Torso	2	**-1**	1
Weight	1	**0**	-1
Latency	3	**1**	-1
Cost	1	**1**	-1
Availability	1	**1**	-1
Mobility of Participant	3	**-1**	1
Complexity	3	**1**	-1
Total		**5**	-6

Logic Controller	Weights	Arduino	Raspberry Pi	Particle Photon
Cost	1	1	**0**	-1
Size	2	1	**0**	1
Clock Speed	3	-1	**1**	-1
Language	2	1	**1**	1
Total		2	**5**	0

Head Piece	Weights	Headband	Baseball Hat	Head Straps
Restriction	3	**1**	0	-1
Weight	1	**1**	-1	0
Ease of Sensor Attachment	2	**0**	-1	1
Snugness	3	**1**	0	1
Adjustability	2	**1**	0	0
Complexity	3	**1**	0	1
Total		**12**	-3	5

Torso Piece	weights	Vest	Climbing Harness
Restriction	3	**0**	1
Weight	1	**-1**	0
Ease of Sensor Attachment	2	**1**	-1
Snugness	3	**1**	1
Adjustability	2	**1**	1
Complexity	3	**1**	0
Storage	1	**1**	-1
Total		**10**	4

Legs and Arms	Weight	Velcro Straps	Buckle Straps
Restriction	3	**1**	0
Weight	1	**0**	0
Ease of Sensor Attachment	2	**1**	1
Snugness	3	**1**	1
Adjustability	2	**1**	1
Complexity	3	**1**	0
Total		**13**	7

Figure 12: This figure shows the various Pugh charts that were created to evaluate our final designs. Pugh charts were created for the subsystems of vibrotactile feedback, the logic controller, the head piece, the torso piece, and the legs and arms of the participant.

Vibrotactile Feedback

Vibrating tactors were the only remaining feedback mechanism after we ruled out skin stretching and electric shocks to the participant. Vibrotactile feedback was broken up into wired and wireless vibrating tactors. The benefit of wireless tactors is that they do not restrict the participant by adding wires between some central logic controller and the extremities of the participant. All sensors used to gather data on the gait of our participants are already wireless so making the tactors wireless would remove wires from the entire design. However, wireless tactors do not exist on the market and are far more complex than wired coin tactors which are readily available.

Wireless tactors could justify a project by themselves, this was an area of discussion between us and our stakeholders. Safa Jabri, one of our stakeholders, was interested in the development of a wireless tactor for use in Dr. Sienko's lab and suggested changing the direction of the project to the development of a wireless tactor. The group decided to continue along the path of creating a full vibrotactile device, so we will be using the wired tactors to keep our project within the scope of this semester. An ideal version of our device may have these wireless tactors to allow for more freedom of movement for our participants.

Logic Controller

The remaining logic controllers left to evaluate were an Arudino, a Raspberry Pi, and a Particle Photon. The Raspberry Pi ended up being the best choice of the group because of its fast clock speed and availability. Dr. Sienko's lab had a Raspberry Pi available for us to use which impacted our decision in choosing it. The Raspberry Pi is also a faster controller than the Arduino and the Particle Photon. This is important because we want as little latency as possible when delivering feedback to the participant. This makes the faster Raspberry Pi the obvious choice among these three controllers.

Head Piece

Our group evaluated a headband, a baseball cap, and head straps (like those used on VR headsets) against each other to pick a final design for what the participant would wear on their head. The head piece needs to be able to hold two tactors, one at the front and one at the back of the head, and also have one sensor attached to gather gait data from the head. The headband was snug, highly comfortable, and minimally complex compared to the other options so we decided to go the route of a headband for our project. It should be a simple matter of attaching two coin motors to the inside of the headband and placing a sensor by the ear of the participant.

Torso Piece

The torso piece is an integral part of the wearable device since it will hold the battery, logic controller, and the implicit feedback array which are some of the most complex and important parts of the wearable device. We compared a generic utility vest (fishermans vest/police vest) to a climbing harness. Other concepts like a hoodie or sweater were eliminated earlier on in the gut check process. While the climbing harness is lighter and has more freedom of movement than a vest, it presents challenges of attaching different components to the torso in a secure way. Because attaching components is so important we ended up choosing a utility vest over the climbing harness.

Legs and Arms

After eliminating the uncomfortable concepts of a full body suit or a sweater and pants, we ended up with tactors and sensors attached to the legs and arms via straps as our remaining concept. Straps are an effective way to attach these tactors and sensors to the body because they are highly adjustable, allowing the researchers to adjust the position where they take data and give feedback to the participant. We were left to decide which kind of straps we would use for these leg and arm attachments. While velcro straps and buckle straps are almost identical, the buckle straps have the potential to be more uncomfortable for the participant than the velcro straps due to the buckle firmly pressing against the participant's skin. Because of this we decided to use velcro straps since those can be tight without any uncomfortable plastic pressing against the participant's arms and legs.

IMU Selection

The final design decision to make was the choice of IMUs to utilize in our design. Table 3. shows the pugh chart created with IMU specs to determine the best IMU for this design project.

Table 3. Pugh chart showing the specifications for the three IMUs benchmarked by our team. IMUs were evaluated based on battery life, cost, latency, size, sampling rate, compatible languages, weight, internal storage, dynamic accuracy, and connection range. The XSens Dot had the highest score at 7 with the other sensors scoring below zero.

IMU	Weight	APDM Opal		XSens Dot		XSens MTw Awinda	
		Value	Specification	Value	Specification	Value	Specification
Battery Life	2	0	8 hours	**1**	9 hours	-1	6 hours
Cost	1	-1	HIGH	**1**	Low (~600 USD)	0	2750 USD
Latency	3	0	30 ms	**0**	30 ms	0	30 ms
Size	1	-1	55 mm x 40.2 mm x 12.5 mm	**1**	36.3 mm x 30.4 mm x 10.8 mm	0	47 mm x 30 mm x 13 mm
Sample Rate	1	0	20 to 128 Hz	**-1**	60 hz	1	1000 Hz
Compatible Software	2	1	Stream to Matlab, Java, Python, C	**0**	Android, IOS, Windows, Raspberry Pi	-1	Awinda Dongle to Windows
Weight	1	-1	< 26 grams	**1**	11.2 g	0	16 g
Internal Storage	1	1	8 Gb	**0**	64 Mb	-1	0
Dynamic Accuray	2	-1	2.80 deg	**0**	1 deg	1	0.75-1.5 deg
Range	3	0	30 m line of sight	**1**	40 m	-1	20 m
Total		-2		**7**		-5	

The obvious choice among the three IMUs our team considered for our design solution was the XSens Dot. In general, the Dot exceeded both of the other options by including the largest battery life, the smallest size and weight, and the largest connection range, all at the lowest cost. Having a battery life of nearly 9 hours allows for daily use of all of the dots with minimum charging. The small size and low weight allows for the Dot to be incorporated easily to the user device without adding any significant weight or redistributing much mass (no significant increase in inertia for any part of the body). Its bluetooth connection range extends over 40 m which is sufficient for testing within the Sienko Research Lab (~40 m long) and a set of 5 sensors is available for the lowest price by a large margin (hundreds compared to thousands of USD).

It also matched the other two sensors in terms of latency and was only disadvantaged in terms of sampling rate. However, a higher sampling rate does not always indicate accurate data collection as higher sampling rates introduce more noise. In fact, the manual for the Dot indicates that the raw data is initially collected at 800 Hz and is later filtered (using a Kalman filter algorithm) to a sampling rate of about 60 hz. Though this method is not infallible, it contributes to reduced error due to noise.

Stakeholder Discussion

Our final filter used in the convergent process was a discussion with our stakeholders to receive feedback on our concept and come up with a singular final design to move forward with. Some of the feedback we received on our preliminary design from our primary stakeholders, Dr. Sienko and Safa Jabri, are described below. Figure 13 shows the initial version of the design shown to the stakeholders.

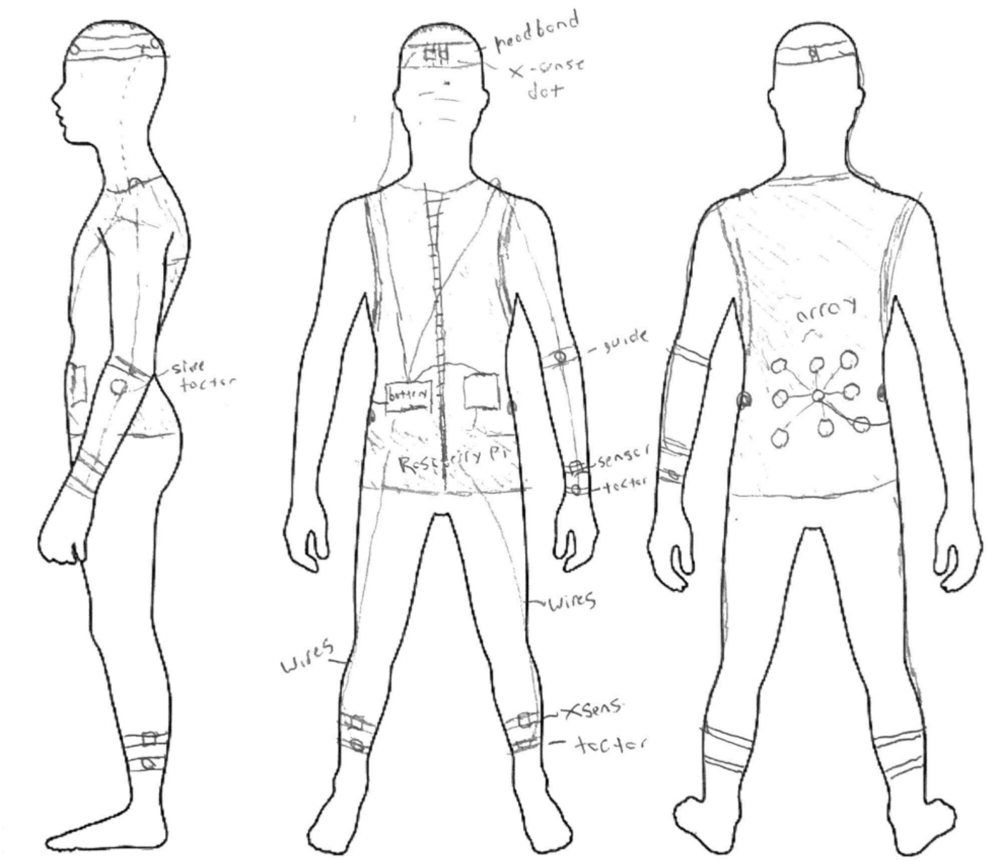


Figure 13: This figure shows the preliminary final design that was brought to our stakeholder meeting to be evaluated by Dr. Sienko and Safa Jabri. Changes to this design are described below.

The first recommendation was to remove zippers from our vest in favor of straps that go around the side of the vest and tighten around the torso, similar to a life jacket. The reasons for this recommendation are twofold. First, the zipper could get in the way of the implicit feedback array on the torso and make it difficult to connect the tactors to the controller. Second, zippers do not provide enough snugness and could result in bad contact between the tactors and the skin which would compromise our solution.

A second recommendation was to make sure that the tactors attached to the headband are reconfigurable. Individuals with larger or smaller heads could end up having one of the two tactors attached to the headband on the side of the head instead of the back or front of the head. Ensuring that feedback is delivered to the front and back of the head every time will help make our design more consistent and reliable.

A third recommendation was to separate tactors and sensors onto different straps. Vibrations from the tactors could easily interfere with the data collection of the sensor and render the feedback useless. Separating the sensors and tactors is important to isolating the sensor data from the vibrations given to the participant.

A final recommendation was to think more about the electrical connections that are used between the tactors and logic controller. Specifically, having tactors that can easily unplug from the controller will make the device less cumbersome and easier for both the researchers and the participants to use.

These recommendations were all taken into account for our final design which is described in the Alpha Final Design section of this report below.

Alpha Final Design

After completing our concept generation and selection method, our team was able to settle on an alpha final design. This design solution is seen as the ideal outcome for our team, and may fall outside of the scope of the ME 450 course.

General

The general layout of the device is shown in Figure 14. This design utilizes 15 tactors, 5 IMUs and separate arm and leg bands for the IMUs and tactors.

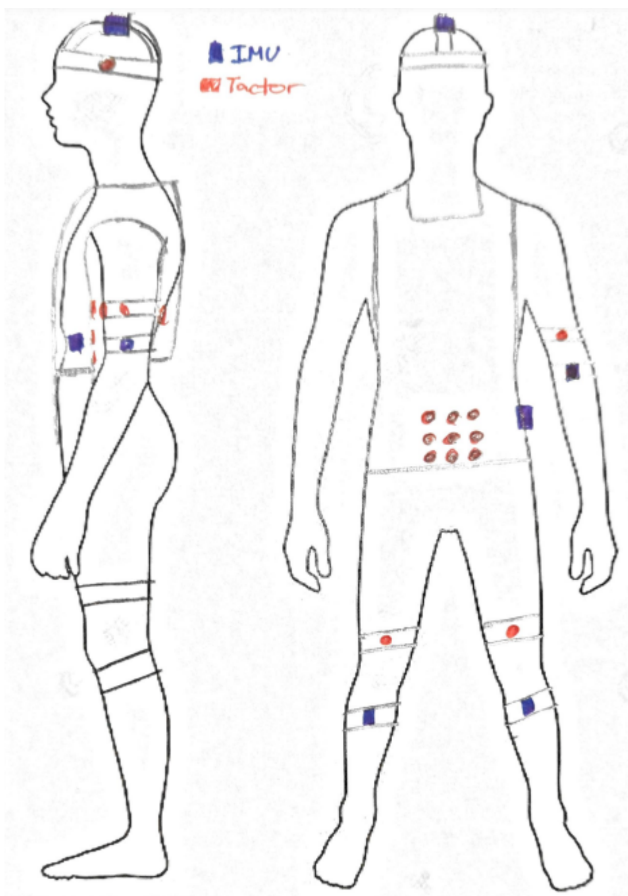


Figure 14. General concept design for vibrotactile feedback device showing the sensor and tactor locations. On the torso is the haptic three-by-three tactor array. IMUs and blue, while the tactors are red. Wiring has not been modeled in this drawing, but all the tactors are wired, while the IMUs communicate with the system wirelessly.

The layout of this design is rather simple, as the arm bands will be moveable allowing for a researcher to fix the IMUs and tactors to different locations on the arms and legs. This provides a way for the researcher to reconfigure the device for both different body sizes and different research areas. Finally, since each device is independently attached, it would allow a researcher to select which tactors and sensors to use for a trial if they did not want to use the entire system to test a certain type of feedback and the effect that it would have on the participants' gait cycle.

Leg and Arm Straps

The design for the leg and arm straps must account for different sizes of these limbs from participant to participant as well as account for different locations. However, these straps have been generalized to one common type, meaning the arm and leg straps will be the same design. Figure 15 shows a drawing of what these bands will look like.

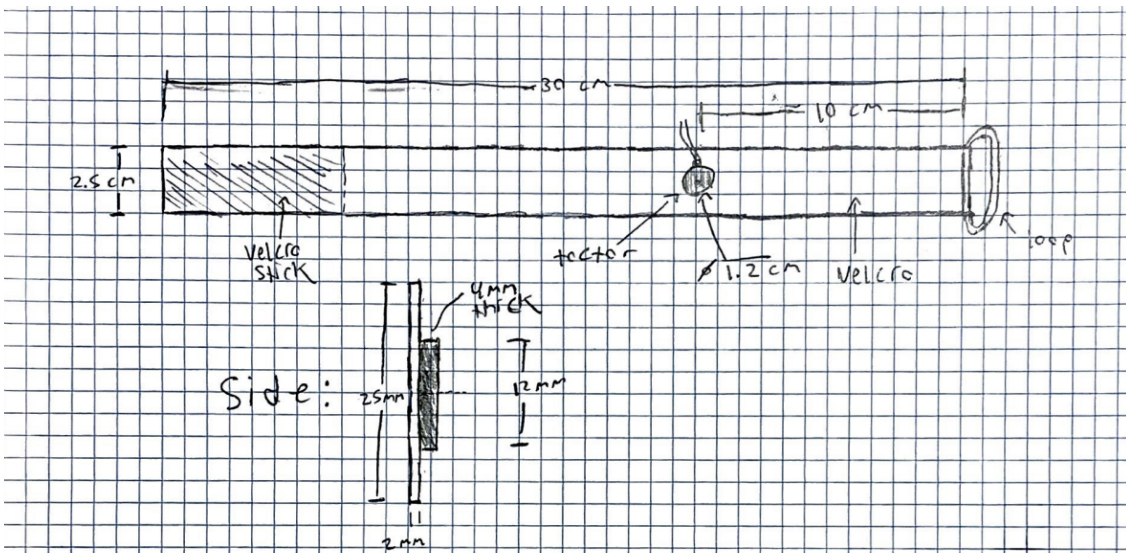


Figure 15. Leg and arm straps to be utilized for alpha final design. The strap is made of velcro with a loop at the end to help hold the strap tight. The tactor can be mounted anywhere on the interior side of the strap to allow for good contact with the skin.

Velcro was chosen as it provides a simple system for tightening while also having good results for tightness. Also, to mount tactors to the strap, velcro is added to the back of the tactor which will enable a researcher to move the tactor depending on the size of the participant's arm or leg. Overall, this concept provides an easy way to reconfigure feedback locations on the arms and legs while also being a simple way for the researcher to attach the tactors.

Head Mount

The head is another important location for not only feedback but also IMU. The device developed for the head is shown in Figure 16, consisting of two tactors on either side of the head and an elastic headband.

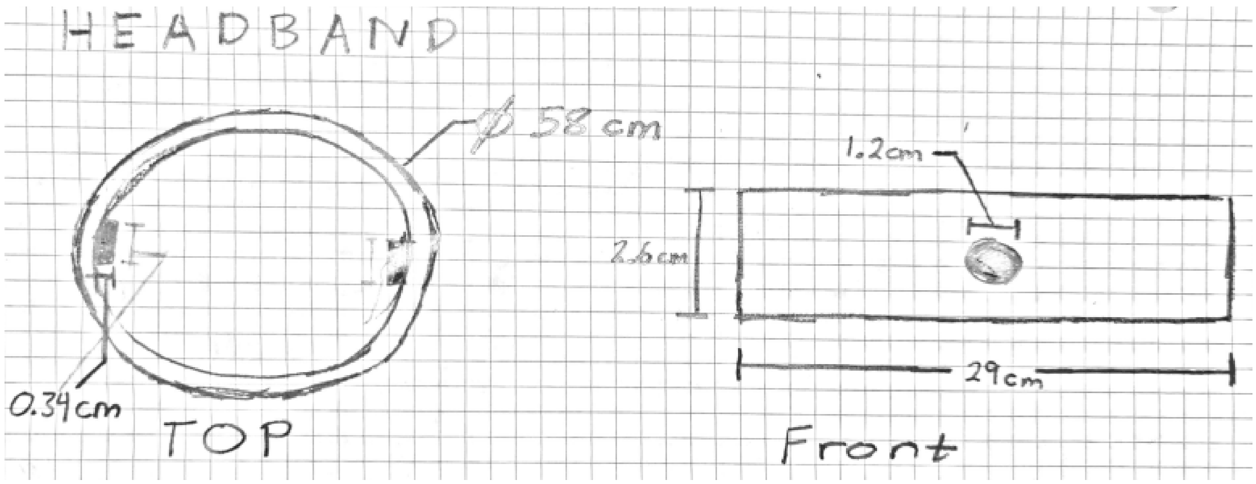


Figure 16. Headband unit for our vibrotactile feedback system. This consists of the two coin tactor motors on both sides of the head attached to an elastic headband. Again, the tactors will have an adhesive on the back that will allow the researcher to change their positions due to changes in the head size.

This head mount allows for simple reconfiguration of the device through the use of the elastic band. This band stretched has a radius of 58 cm, which makes it easily conform to the specifications that our team has created. Furthermore, by allowing the researcher to reposition the tactors on the interior of the headband, it allows them to change to front and back tactor locations as well as left and right side tactor locations depending on what their tests are. Overall, this head mount design for the tactors will provide the proper reconfigurability in both researcher testing modes and changing participants between trials.

Vest

The vest component of our design is essential as it houses the implicit vibrotactile display, as well as our central logic processing unit and the battery that will supply power to all of the tactors. Figure 17 shows a top view of the vest while Figure 18 shows the front and side views.

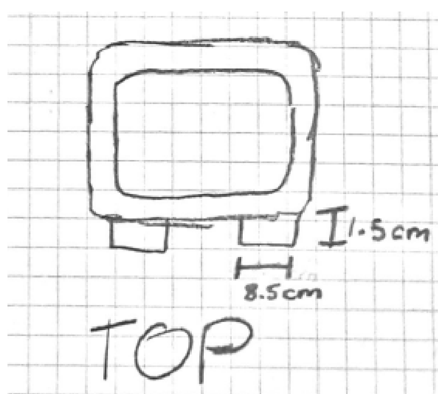


Figure 17. Top view of the vest design. Supports will go over each shoulder and pockets are on the front of the vest to house the logic center as well as the battery that will power all the wired components.

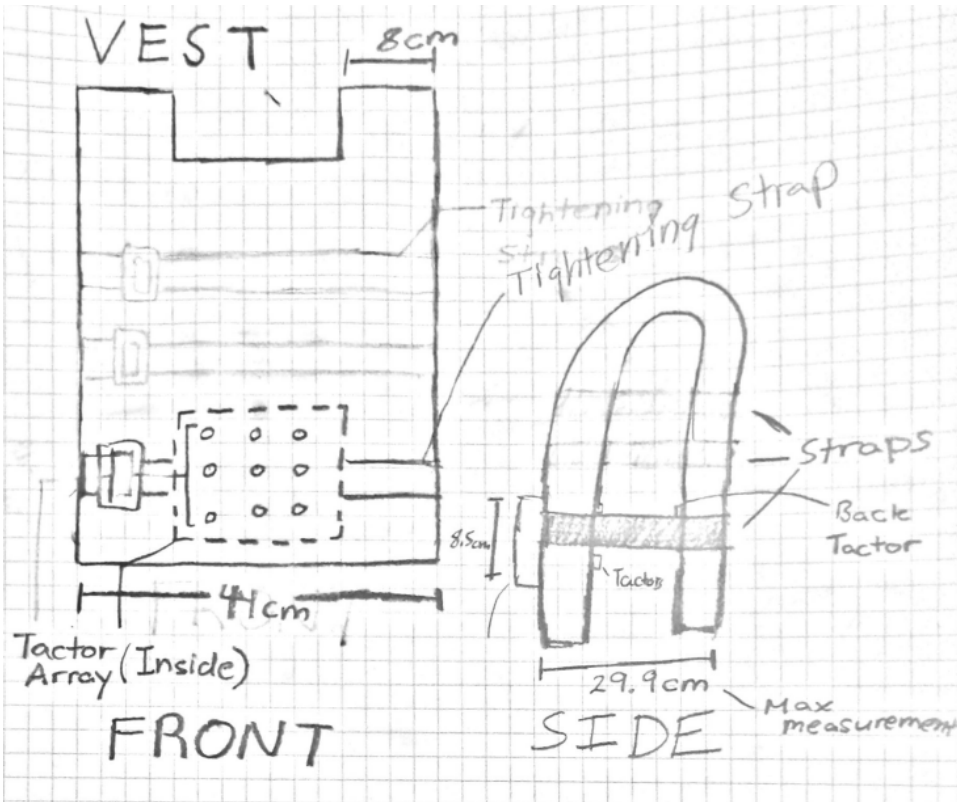


Figure 18. Front and side views of the vest component of our device. The vibrotactile three by three tactor array is housed on the interior of the vest, with a tightening strap around the waist to ensure good contact between the tactors and the participant's skin. A tactor is also placed on the interior of the back of the vest to allow for explicit feedback modality.

A vest design was chosen due to it being easy for a researcher to put on a participant as well as allowing for the positions of the tactors to stay steady. Another concern that was alleviated with a vest is the distribution of weight, as most devices to date center around a belt that carries most of the weight, while a vest in our case will distribute this weight all over the participant's body. The vest design also allows for convenient storage of the logic center and battery through the use of pockets on the front face. These pockets can also house some excess wiring, and preparations are being made to have more locations to store wires on the device.

Tactors for Implicit and Explicit Display

The tactors of our design provide the means of vibrotactile feedback for both the implicit and explicit feedback modes. Figure 19 shows a top and bottom view of a single tactor.

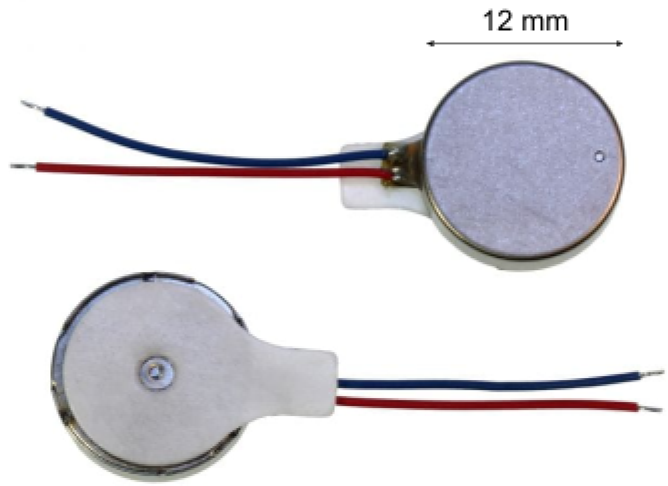


Figure 19. Solarbotics VPM 2 coin motors for Implicit and Explicit vibrotactile feedback. They are fairly small in size with a diameter of 12 mm and a thickness of about 3.4 mm. They feature two pre-soldered leads and adhesive on one side for easy mounting to a smooth surface.

These tactors are capable of delivering 150-250 hz vibrations given standard operating voltages which is well within the range determined for both the implicit and explicit feedback specifications (vibrations between 60-300 Hz). These vibrational frequencies encompass the range of vibrations detectable by most people such that they can discriminate between two different locations of vibrational contact. This is especially important for the tactor array located on the vest portion of the device since there will be a group of tactors in a common region of the body. Therefore, the VPM 2 motors give the desired and necessary vibrational frequencies in which research participants will be able to detect distinct points of feedback.

IMU

The inertial measurement units collect and provide rotational and linear motion data that is used to determine when and where the user device will give feedback to the user. The data must be accurate and precise in order for any of the feedback from the tactors to be useful for the user. They must not hinder or affect the movement of the user. Engineering drawings of the XSens Dot IMUs are provided in figure 20 below.

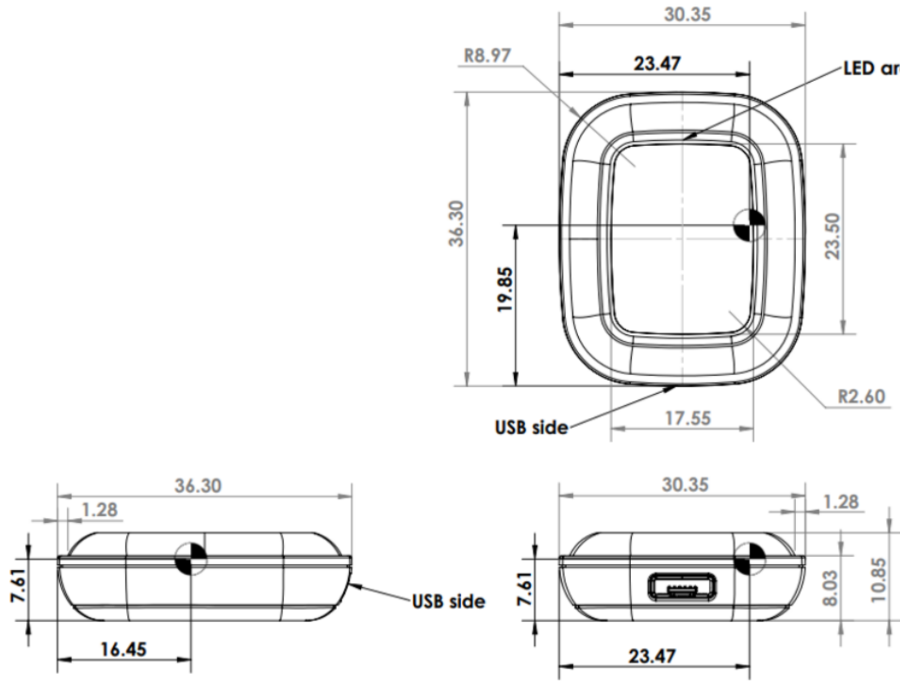


Figure 20. Engineering drawing of the XSens Dot IMU. The XSens Dot IMUs are compact in size and simple in shape which makes them excellent for easy and portable storage within our design solution.

The XSens Dot IMUs are compact in shape and size and connect wirelessly to a mobile device via bluetooth or an online server via wifi, making it easy to incorporate them into the lightweight design of our current solution. The wireless feature also decreases the total wiring on the user device which contributes to less necessary wiring management. These IMUs also last 9 hours on a full charge which allows for multiple participant trials per day (assuming ~1 hour maximum per participant) before requiring more charging time. They collect data at a maximum of 30 ms of latency and have an output sample rate of 60 hz (after Kalman filtering) which should produce low-noise data. They also come in sets of five with a common charging case that allows for simultaneous charging of all the sensors.

Wiring Design

The wiring design currently developed has factored in connections from the Raspberry PI 4 all the way to the coin tactor. The design is meant to capture more permanent connections to the actual Raspberry PI and more modular connections when attaching at each of the locations. In Figure 21. the wiring design is laid out in order from the PI to the coin tactor.

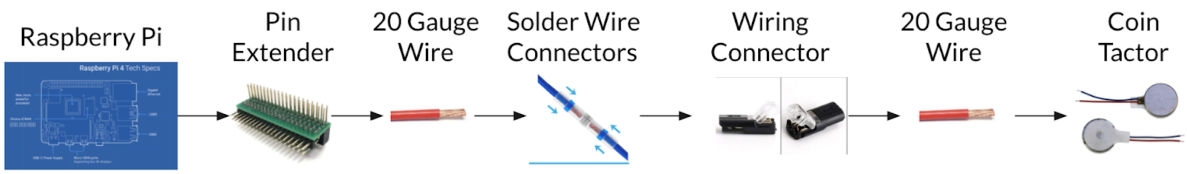


Figure 21. Sample Wiring Design, showing the electrical flow from left to right, from the raspberry pi to the coin tactor motors.

To start, the pin extender attaches into the Raspberry PI which allows for more flexibility in where we make the connections but also allows for more permanent connection since some sort of solder can be applied. Next, the solder wire seal connectors allow for a connection to be made while protecting the wire with a shrink tube. After, the wire attached to the wiring connector that is meant to click after the connection is secure. This will serve as the bridge between coin tactors and the more permanent PI connections. This would allow for one to put the device on first and then click the connectors into place that correspond to the correct location labeled to the PI.

Design Concerns

The design concerns associated with this project will be helpful for DR3 when we will be outlining a risk plan. These are all valid concerns we should be aware of but also some have been addressed by our choice of engineering analysis to help move the group forward in the right direction.

System Compatibility

Since our design solution involves multiple subsystems interacting with each other in real-time, it is very important that each subsystem is compatible with one another. The most apparent potential sources of compatibility issues are for interactions between the XSens Dot IMUs and the Raspberry Pi, and the Raspberry Pi and MATLAB.

The XSens Dot IMUs are largely app based in design and are meant to record and livestream motion metrics from a mobile device, such as a phone or tablet (they can also record offline to the IMUs but this function is not useful for our application). The collected data is inaccessible during real-time data recording and livestreaming to the mobile device while using the Dots in its most intended way. However, there is a way to access the data live from a server provided by XSens that can connect to a raspberry pi. The concern with this method is that it may take longer for the collected data to be translated into feedback commands sent to the motors compared to if the data can be sent straight to the Raspberry Pi. The data transfer to and from the XSens Dot server introduces an extra step for live data processing (possibly introducing latency) and brings a higher level of programming complexity that our team has not encountered before (due to the lack of more advanced programming/computer science experience).

The other apparent potential source of compatibility issues involves the interactions between the Raspberry Pi and MATLAB. After data is collected by the sensors, moved to the XSens Dot server, and retrieved by the Raspberry Pi, the data must transfer from the Raspberry Pi to MATLAB (likely on the researcher device) and back to the Raspberry Pi, so that the Raspberry Pi can send output signals to the tactors based on the collected data. The back-and-forth of data transfer still leads to the problem of too much latency again, but the larger concern comes from the complexity of these connections. Based on our research and basic knowledge of MATLAB, our team knows that these interactions between the

Raspberry Pi and MATLAB are possible in theory. Our team is unsure at this point if these methods that we intend to pursue are realistic or even the best ways to connect these systems and direct the flow of data, given the amount of software setup that seems to be required.

Wiring

Since our design involves electrical connections between components that will run along the body of a research participant, we need to be able to ensure that the wiring does not break or limit the mobility of the participant during gait trials.

The issue of wiring not being properly connected or connections breaking during a trial is one that could prove disastrous. Not only could loose leads shock the participant, but if the device does not function properly during trial runs, proper feedback may not be delivered and a participant that has gotten used to feedback may fall due to not receiving it. Furthermore, it has been requested from stakeholders that the device make use of a system that allows for easy attachment and detachment of sensors. These connections must also be strong enough to hold up to testing while also not running a risk of sending electrical shocks to the participants, but still be easy enough to detach in a quick manner.

The other main issue with the wiring is the restriction of movement and the trip hazard it may cause. This can be due to wires being too tight restricting motion, or wires dangling from the body of a participant causing them some discomfort. Making sure that the wiring is the proper length is the best way to ensure that the device does not create a potential fall hazard. The wiring cannot be too tight or loose, so testing the device and having methods to retract wires built into the vest component of the device appears to be the best way to combat this problem.

The durability and reconfigurability of our device wiring and the wiring connections are a potential concern that will be monitored throughout the design process to ensure a safe device for both the participants and researcher.

Accurate Sensor Capturing

The ability for the IMU sensors chosen to relay accurate, precise data is important to providing the correct feedback to the participant wearing the device. The sensing of the kinematics of a participants gait cycle hinges on the IMUs chosen being able to accurately track the cycle with the locations that have been outlined. The concern in this case is the selected IMUs despite being used for other forms of motion tracking revolving around athletics, where they are only trying to capture the kinematics and not provide the data in real time to another device. If the sensors are not accurate enough, then the feedback provided will be incorrect, the same would occur if the precision that we code the device to provide feedback is not met by the sensors then we would also start to provide incorrect feedback. Therefore, being able to ensure that the sensors accurately capture the gait of a participant is a concern, as the device's ability to provide feedback directly hinges on the sensor input information.

Tactor Contact

The tactors contact with the skin is critical for ensuring responsive feedback that is usable. This would make us focus more on the way the tactors are fastened to the straps but also how secure those straps are with the participants who put these on. Our concern would be if we can’t maintain a good contact at all of our tactor locations the user will have a harder time interpreting the feedback we are trying to provide. The participants movement can affect the way things are fastened resulting in contact.

Programming
The programming portion of this device involves creating a way to take the IMU inputs and translate the inputs to signals that will be accepted by the tactors on the device and provide vibrotactile feedback to the participant. If we cannot create a code that does this in an efficient manner with low latency then we will not meet the real time feedback requirement that we have been given. However, our group does not have much experience coding outside of the matlab language, and most devices that have used the XSens Dots utilize python or android operating systems to communicate with the user interface. Our group's lack of experience is cause for concern as learning new programming languages can be difficult when a user does not have a lot of experience.

Plan for Engineering Analysis

Theoretical
Theoretical engineering analysis can be very valuable for making decisions without actually having to run physical tests. In our situation, the theoretical analysis will help guide our design and the parts we choose to purchase.

Battery Capacity
The battery capacity is vital to keeping the device operating. Now that we have chosen a Raspberry PI 4.0 for the design and the tactors we can perform a good estimate of the portable battery capacity needed. The IMU sensors have individual batteries for each location meaning they will not be factored into this battery analysis. Our benchmark will be up to 1 hour of continuous use to begin. In order to predict the worst-case scenario, we will assume the tactors will be spinning at the max level for calculations. This amount of power is combined with the Raspberry PI 4.0 will guide us to the proper battery size.

Wire Force
The force that is exerted on the different connections across the body from a participant walking can cause wires to become detached. The amount of force can be estimated through research articles which will help guide the amount of clamping force required by a connection to ensure attachment.

Empirical
Some components of our vibrotactile design have been identified to be more feasible to test empirically. This section will deal with explaining the thought process behind choosing this route for the described areas of design while also outlining the preliminary plan to conduct these tests.

Tactor Activation
To start, the first area that will need to be tested empirically is the connections of the tactors to the Raspberry Pi 4.0 logic controller. This is because we must prove that our device can achieve activation of multiple sensors at once, but more importantly we need the ability to activate individual tactors independent of each other. For example, the type of explicit feedback that a researcher may want to conduct may only call for the use of feedback on the head. By testing tactor operation and ensuring independence, we will prove that this researcher's need is achievable.

To conduct this analysis, we will start by wiring the device to have only one tactor and ensure that we can activate it. Next we will gradually double the amount of tactors that are wiring, first to 2, then 4, 8, and then finally 15 tactors. Ensuring that we can activate these tactors by themselves early in the design process will help with our proof of concept for our design. Tactor activation is also essential for a participant, especially in the explicit case. If the tactors malfunction, activate in an undesired way, or just provide false feedback, someone using the device to go through moving gait may be at an increased fall risk. To alleviate some of these concerns early, we need to test these tactors for their functionality and capability to be activated independently. This will also test our ability to code in the Raspberry Pi - MatLab interface that we are trying to use.

IMU Testing

The next set of empirical tests that we can use involve working with the IMUs selected and the Raspberry Pi. We first need to test the IMUs to make sure that their tracking of gait is sufficient with the requirements and specifications that have been developed over the course of this project development. To do this, we will first use the XSENS app to gather data through the system developed by the makers of the IMUs. This will act as a control that we can test against when we establish the connection between the IMUs and Raspberry Pi. After this data has been collected, we turn to creating the Raspberry Pi code and establishing a connection between the XSENS Dot IMUs and Raspberry Pi. The Raspberry Pi logic controller has onboard capability to log data through the use of an SD card, so to start we will use this method to collect data. Once we have made sure that the data can be collected by Raspberry Pi, we move on to establishing a connection between the logic controller and the computer.

Testing this connection will be very important. We want to be able to show early on that we can stream the data from the IMUs to the Raspberry Pi and then to the researcher UI on the computer. Once we have established this connection, we will have one individual in our group wear the IMUs one at a time and check that the data streaming to the computer matches up with our previous collected data through the use of the XSENS app, as well as through the tracking and storing on the Raspberry Pi SD card. Once this has been done for the 5 mounting locations, we can move on to establishing a connection with all 5 IMUs active, and showing that the Raspberry Pi can handle this large of a data stream.

Researcher UI Testing

Once the IMUs and tactors have been independently tested of one another, the team will then be able to move to testing the researcher UI and its ability to change the test states. This involves adding and removing feedback locations, IMUs or changing the implicit pattern that will be displayed on the torso through the use of the vibrotactile feedback that we developed.

To test these things, we must first work with the researcher UI to show that we can change these patterns, locations and input other information like age, name, sex of the participant. Once we have a UI that has a place for these inputs, we can then test the ability for the UI to make these changes to the physical device. This will be done by a member of our group wearing the device while someone else acts as a researcher, changing the test parameters and logging data. Doing this process will allow us to show that in both cases, the researcher and participant, that the device is able to reconfigure itself while attached and take data that is meaningful to what a researcher is testing. Therefore our final empirical testing step needs to be a full system check to ensure that the device that we hand off to the Sienko Research Group is fully functioning.

Detailed Design Solution

Our final design solution consists of two main parts, the physical device and the researcher UI that controls the feedback parameters of the device. For the purpose of the ME450 course, this section details the two distinctions between what is envisioned as the final solution for the course, and the final solution that would be completed for a product to go onto the market. This distinction is made in terms of components, and again is mainly centered around the researcher user interface.

ME450 Final Design Solution

Our final design solution in the context of the ME450 course consists of a physical device and the basic Matlab UI to change parameters of testing. These two systems have to work together to produce a valid vibrotactile feedback device to be used for gait research. In figure 22, an image is presented showing the locations of the IMUs and tactors.

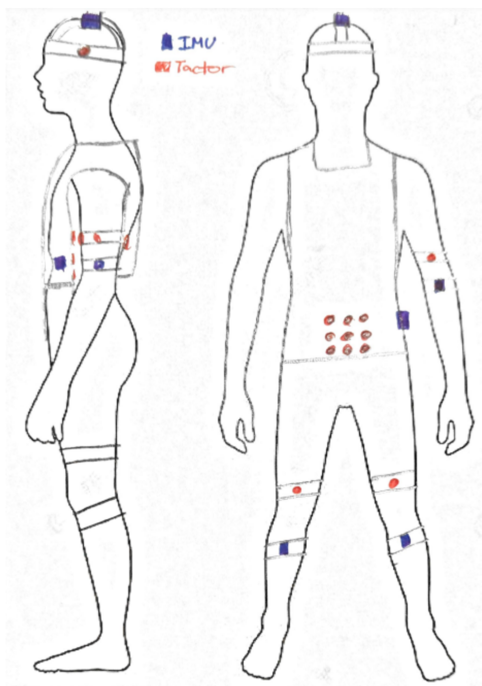


Figure 22. Location diagram for tactors and IMUs. The implicit vibrotactile array is on the inside of the vest on the torso.

As shown in the figure, the locations for both the IMUs and the tactors have been finalized. These locations are chosen to provide the researcher with the valuable information and data that they need to provide proper vibrotactile feedback. The locations were requested by our stakeholders. Wiring will run to all the tactors from the torso, where the logic center and battery will be located inside of a pocket of the vest, while the IMUs are wireless.

The vibrotactile array that is placed on the torso is another part of our design that is important as it is the mode in which we will deliver implicit vibrotactile feedback to the participant wearing the device. Figure 23 shows the vibrotactile array that will be placed on the torso.

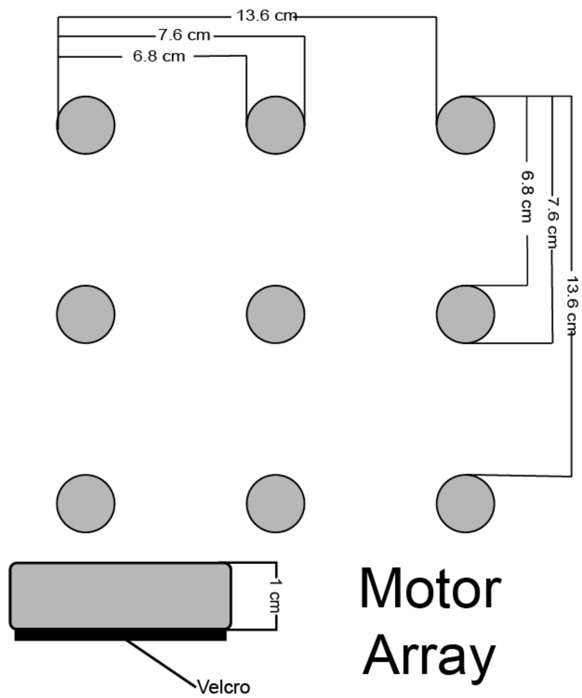


Figure 23. Vibrotactile array that will be on the torso of the device. This array contains 9 coin motors that are separated edge to edge by 6 cm to allow for proper two point discrimination values to be upheld, as stated by our requirements and specifications

This implicit array will have multiple patterns assigned to it, with the researcher able to create these patterns based on what GPIO pins must be activated on. Each motor in the entire design will have velcro attached to the back of it to be attached on the inside of the vest component of our device. The vest is a component of the design that was bought externally, like many of the components that are to come in the remainder of this report. An image of the vets chosen is shown in Figure 24.

Figure 24. The vest by Himal Sports to be used in our device design. This vest was chosen as it has many pockets to be used for storage of electronic components like the logic center. This also contains a strap around the waist that can be used to help tighten the array to the midsection of the participant wearing it.

Tactors must also be attached on the arms and legs, for these areas, the straps in Figure 25 will be used, as they are made of velcro and will allow for easy tactor attachment.

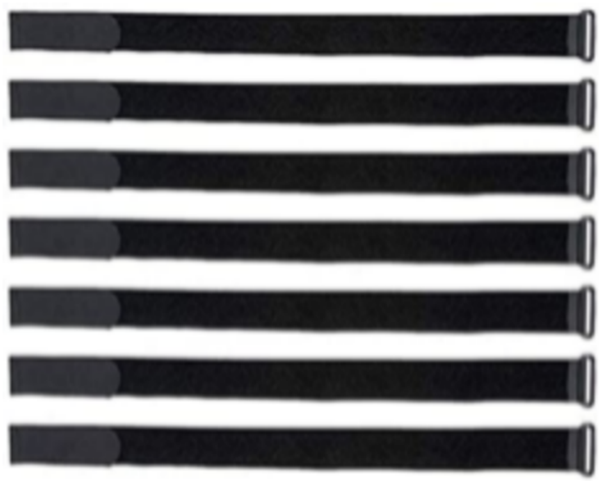


Figure 25. Velcro straps made by VELCRO Brand. They measure 30.34 cm in length by 2.54 cm wide. These straps will need to be placed on the arm of participants with the soft velcro side closer to the skin, allowing for the tactor velcro on the back to be attached to the soft side of the band.

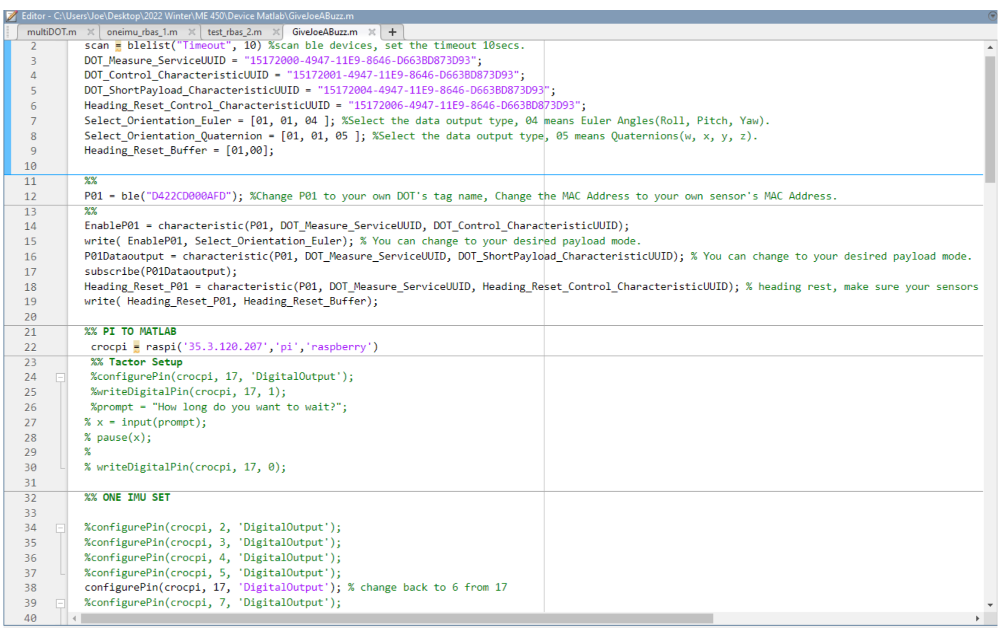
The last part of the design where tactors will be attached is on the head. These attachments will most likely need to be with a tape adhesive as the bands for the head are not made of velcro. The headband chosen can be seen in Figure 26.

Figure 26. The headband to be used to attach tactors to the head. This headband is made by LUCKYGO and is elastic, meaning it can stretch to different head sizes. Unstretched, the band has a size of 23.78 cm by 6.10 cm.

With the headband selected, the final components needed are for the electrical system. For information about the logic centers, IMUs, and the coin tactor motors chosen, refer to their respective section in the Engineering Analysis - Component Selection section of this report. However, to connect the tactors to the logic center, wiring will be used. These wirings must be detachable as per the reconfigurable requirement from our stakeholders. Figure 27 is a flow chart showing how the wiring connections will work, from the logic center to the battery.

Figure 27. Wiring connection flow chart, from left to right you have the Raspberry Pi, through wiring from Plusivo, then to the wire connectors, and finally the coin motors, INEED C0820BE03L27, are crimped onto the wire connectors.

Finally, to address the researcher UI, the team plans to use the Matlab user interface and command window for researcher manipulation of test parameters. In Figures 28 and 29, an example of what the Matlab code will look like is shown.



Editor - C:\Users\Joe\Desktop\2022 Winter\ME 450\Device Matlab\GiveJoeABuzz.m
multiDOT.m | oneimu_rbas_1.m | test_rbas_2.m | GiveJoeABuzz.m

```
scan = blelist("Timeout", 10) %scan ble devices, set the timeout 10secs.
DOT_Measure_ServiceUUID = "15172000-4947-11E9-8646-D663BD873D93";
DOT_Control_CharacteristicUUID = "15172001-4947-11E9-8646-D663BD873D93";
DOT_ShortPayload_CharacteristicUUID = "15172004-4947-11E9-8646-D663BD873D93";
Heading_Reset_Control_CharacteristicUUID = "15172006-4947-11E9-8646-D663BD873D93";
Select_Orientation_Euler = [01, 01, 04 ]; %Select the data output type, 04 means Euler Angles(Roll, Pitch, Yaw).
Select_Orientation_Quaternion = [01, 01, 05 ]; %Select the data output type, 05 means Quaternions(w, x, y, z).
Heading_Reset_Buffer = [01,00];

%%
P01 = ble("D422CD000AFD"); %Change P01 to your own DOT's tag name, Change the MAC Address to your own sensor's MAC Address.
%%
EnableP01 = characteristic(P01, DOT_Measure_ServiceUUID, DOT_Control_CharacteristicUUID);
write( EnableP01, Select_Orientation_Euler); % You can change to your desired payload mode.
P01Dataoutput = characteristic(P01, DOT_Measure_ServiceUUID, DOT_ShortPayload_CharacteristicUUID); % You can change to your desired payload mode.
subscribe(P01Dataoutput);
Heading_Reset_P01 = characteristic(P01, DOT_Measure_ServiceUUID, Heading_Reset_Control_CharacteristicUUID); % heading rest, make sure your sensors
write( Heading_Reset_P01, Heading_Reset_Buffer);

%% PI TO MATLAB
 crocpi = raspi('35.3.120.207','pi','raspberry')
 %% Tactor Setup
 %configurePin(crocpi, 17, 'DigitalOutput');
 %writeDigitalPin(crocpi, 17, 1);
 %prompt = "How long do you want to wait?";
% x = input(prompt);
% pause(x);
%
% writeDigitalPin(crocpi, 17, 0);

%% ONE IMU SET

%configurePin(crocpi, 2, 'DigitalOutput');
%configurePin(crocpi, 3, 'DigitalOutput');
%configurePin(crocpi, 4, 'DigitalOutput');
%configurePin(crocpi, 5, 'DigitalOutput');
configurePin(crocpi, 17, 'DigitalOutput'); % change back to 6 from 17
%configurePin(crocpi, 7, 'DigitalOutput');
```

Figure 28. The first part of the Matlab code. The first section establishes a bluetooth connection between matlab and the XSens Dot, which in this example is only one IMU. The second section determines what data Matlab will receive from the dots, and then establishes the connection to the Raspberry Pi logic controller.

```
for i=1:count
    P01data = read(P01Dataoutput);

    P01Roll(i)= rollConvert (P01data); %Roll
    P01Pitch(i)= pitchConvert (P01data); %Pitch
    P01Yaw(i)= yawConvert (P01data); %Yaw

    tiledlayout(3,1) % Create a 3x1 plot

    ax1 = nexttile; % First plot
    plot(ax1,P01Roll,'red')
    title(ax1,'Plot 1')

    ax2 = nexttile;
    plot(ax2,P01Pitch,'red')
    title(ax2,'Plot 2')

    ax3 = nexttile;
    plot(ax3,P01Yaw,'red')
    title(ax3,'Plot 2')

    % write thresholds for implicit array from trunk sway
    T1 = 20; % degrees
    T2 = 30; % degrees
    T3 = 40; % degrees

    % this is where we chance thresholds and rules ->
    if ((P01Roll(i) > 80) && (P01Roll(i) < 100))

       % writeDigitalPin(crocpi, 2, 0);
        %writeDigitalPin(crocpi, 3, 0);
        %writeDigitalPin(crocpi, 4, 0);
        %writeDigitalPin(crocpi, 5, 0);
        writeDigitalPin(crocpi, 17, 0);
        %writeDigitalPin(crocpi, 7, 0);
        %writeDigitalPin(crocpi, 8, 0);
        %writeDigitalPin(crocpi, 9, 0);
        %writeDigitalPin(crocpi, 10, 0);

    else if ((P01Roll(i) > 100) || (P01Roll(i) < 80))
```

Figure 29. The second part of the test code, which shows the setup for how IMU data will activate a single tactor.

With the researcher UI being the native Matlab UI in the case for our device for the end of semester handoff, the solution to turn tactors off or on is to comment the lines out and then detach the tactors from the rest of the device shown in the wiring connection flow chart. Through having this method to enable and disable tactors, we once again can meet the requirement of being reconfigurable.

To Market Final Design Solution

The main difference between the solution presented to the Sienko Research Group at the end of the ME450 class and the solution envisioned by our group deals with the researcher UI. As detailed in the previous section, the UI in the state that the device will be handed over is just a Matlab code with detailed comments on what lines to change and what the changes will mean. However, the ideal solution would be to have a phone app that can control the device, with the ability to select feedback locations, IMU tracking locations, as well as the implicit feedback pattern. An example of what this may look like is shown in Figure 30.

Figure 30. A sample of what a phone app may look like to be used with the research device. This was visualized in Photoshop and does not represent any actual coding in the IOS or Android coding schemes.

As shown in Figure 30, a phone app acts as an easier way for the researcher to change the parameters of trials during gait cycle vibrotactile feedback research. At the top, a section is available to enter the name and other distinguishing information about the participant. Then Active IMUs can be selected in the next section. Next, the Feedback settings are shown, with explicit feedback for each location having the ability to be turned on and off. Underneath that implicit feedback patterns are listed, and notes can be written by the user about what the patterns are. The idea here is for the researcher to have the ability to code different patterns into the logic center outside of the app, so the implicit feedback would have a different way to change the parameters not involved in the app. The start and stop buttons at the bottom function to start and stop testing, while the save function allows the researcher to save the data from the previous interval between pressing the start and stop buttons. New file will be used to create a new file for a new participant wearing the device, and the restart button functions as a way to restart a trial while it is in progress.

Overall, this phone app design serves as the final desired solution that lands outside the scope of what our team will be able to accomplish this semester. However, it does represent a future version of our concept that could be used to create an easier way for the researcher to change trial parameters and help improve the reconfigurability of the device.

Engineering Analysis - FMEA

The FMEA analysis method is often used with medical devices to categorize potential hazards that may arise due to the operation of the device. With this in mind, our team decided to proceed with an FMEA analysis to help address any safety issues and inform the prioritization of other engineering analysis that is needed to complete and verify a final design. This is an essential step as making sure we acknowledge any risks gives us a better sense of any ethical decisions that will need to be made. Table 4 shows the FMEA analysis conducted by the team.

Table 4. FMEA Analysis used to determine the most important safety concerns. The failure modes with the highest associated Risk Priority Numbers are bolded. A larger RPN indicates more risk associated with the failure mode.

Component	Function	Failure Modes	Effects	Severity	Probability	Detection Rate	Risk Priority Number RPN
IMUs	Track movement data of the user	Unable to connect	No feedback	8	5	1	**40**
		Disconnect during use	No feedback, Fall Risk	10	4	1	**40**
		Lose power in use	No feedback, Fall Risk	10	1	2	20
		Provide inaccurate data	Incorrect Feedback, Fall Risk	7	2	2	28
Battery	Supply Power to the Device	No charge	No Feedback	10	1	1	10
Tactors	Provide vibrotactile feedback	Wiring becomes undone	No feedback, electric shock	7	2	1	14
		Tactors break during use	No Feedback	9	1	3	27
Straps	Attachment of Sensors and Tactors to the body	Straps become undone	No tactor on skin, no feedback	7	2	1	14
		Straps don't apply good contact	Feedback cannot be felt by wearer	7	2	1	14
Wiring	Connect battery, logic center, and tactors	Breaks or becomes undone	Shocks to wearer, no feedback	7	3	1	21
		Coating breaks	Shocks to wearer	7	2	1	14

Logic Center	Process input data and provide signals to the tactors for feedback	Disconnects	No signal processing, no feedback	10	2	2	**40**
		Short Circuits	No signal processing, no feedback	10	2	1	20

Values assigned for severity, probability, and detection rate from Table 4 were multiplied by each other to provide the RPN as a product of the three categories. In each case, a larger number is seen as worse than a smaller number. For example, a 1 on the probability scale means that it is likely to be detected a majority of the time, while a 10 would be highly unlikely or almost impossible to detect the associated issue.

Most issues that could arise through the use of our device are likely detectable, if not easy, and have been assumed to have a low effect on the risk priority numbers, as the largest value for that category is a 3. This was due to our thought that with proper instructions and the researcher's own prior knowledge, detecting any issues that could occur is most likely something that is reasonable to assume.

The probabilities of most failure occurrences are less than 5, outside of disconnection or inability to connect to the IMUs, which were assumed to have values of 5 and 4 respectively due to the nature of wireless connections. These wireless connections, while something identified by stakeholders early in the design process do pose some additional risk. This risk comes from the fact that wireless connections can be affected by interference from other wireless devices, wireless range of the device, and obstructions like walls or doors. Making sure that the IMUs can have a connection that is stable in the face of these disturbances is crucial, and must be an essential design aspect considered when selecting components and building the device.

Severity values for our analysis were on the more severe side, with a highest assigned value of 10 being the most severe consequence, and a lowest value of 7 on the 1 to 10 scale. In the case of providing no feedback under most failure modes, we felt that being more cautious and assigning these higher values illustrates the real concern that could occur for the participant if something were to go wrong with the device prior to or while in use. The severity values were all the highest out of the three categories scored.

From Table 4, it is clear that the IMUs can pose the biggest threat to the safety of a participant that would wear the device during research studies. The IMUs main failure mode has to deal with their connection to the rest of the electrical system. The IMUs track and provide data to the logic center that is then interpreted and fed back to the tactors to provide the vibrotactile feedback. If these IMUs were to disconnect, lose power, provide inaccurate data or even have problems with initial connection to the device, the person wearing the device becomes an even more likely fall risk. This was identified as the effect because the participant wearing the device would most likely be waiting for the feedback and trusting it in the early stages of the research studies that they are participating in.

Furthermore, the other component that has a high risk priority number is the logic center in the case where it disconnects, either wired or wirelessly. The logic center processes all of the input signals from the IMUs and sends on and off signals to the tactors based on the IMU inputs. Therefore, if the logic center was to become disconnected, the no feedback risk would again be assumed and is the reason for the large risk priority number.

Engineering Analysis - Component Selection

Informed by our FMEA analysis, the next crucial analysis that our team decided to pursue was a deeper dive into the selection of components for our design. Currently, there are numerous IMUs, Logic centers, and coin tactors motors on the market that could be used in our design. However, making sure that we are thorough in our selection process is essential to producing a safe design to be used in the Sienko Research Groups research into vibrotactile feedback for gait disorders.

IMU Selection

As shown in the FMEA analysis from earlier, the highest risk priority numbers dealt with the case where the IMUs underwent a failure mode. The IMUs track the movement of the participant wearing the device and provide this data to the logic center which then controls the feedback given to the participant. If the IMU connection to the logic center is disrupted, then feedback cannot be received by the participant. In Table 5, the three IMUs that our group would have access to through the Sienko Research Group are named, and specifications pertaining to each IMU are given along with their rankings.

Table 5. IMU selection Pugh Chart. This chart shows the prioritization of specifications through their weight, on a scale of 1-3, with 3 assigned to the specifications that are most important, and 1 being less important.

IMU		APDM Opal		XSens Dot		XSens MTw Awinda	
Categories	Weight	Value	Specification	Value	Specification	Value	Specification
Battery Life	2	0	8 hours	**1**	9 hours	-1	6 hours
Cost	1	-1	HIGH	**1**	Low (~600 USD)	0	2750 USD
Latency	3	0	30 ms	**0**	30 ms	0	30 ms
Size	1	-1	55 mm x 40.2 mm x 12.5 mm	**1**	36.3 mm x 30.4 mm x 10.8 mm	0	47 mm x 30 mm x 13 mm
Sample Rate	1	0	20 to 128 Hz	**-1**	60 hz	1	1000 Hz
Compatible Software	2	1	Stream to Matlab, Java, Python, C	**0**	Android, IOS, Windows, Raspberry Pi	-1	Awinda Dongle to Windows
Mass	1	-1	< 26 grams	**1**	11.2 g	0	16 g
Internal Storage	1	1	8 Gb	**0**	64 Mb	-1	0
Data Streaming	3	1	Continuous stream for processing	**0**	Stream to XSens App	-1	No
Dynamic Accuray	2	-1	2.80 deg	**0**	1 deg	1	0.75-1.5 deg
Range	3	0	30 m line of sight	**1**	40 m	-1	20 m
Total		1		**7**		-5	

Battery Life

The battery life category has to deal with how long the IMUs can last on a single charge. It was assigned a weight of 2 due to it being important to the device remaining wireless from the research interface, allowing for the research participant to actually walk with the device until devices used for standing balance gait. The XSens Dot IMUs had the longest battery life on a single charge, so were assigned a value of 1.

Cost
Cost is the price of 5 IMUs of the indicated type, as our design requires the 5 IMUs to have the proper input data as requested by our stakeholders. Cost of the IMUs was assigned a value of 1. This was due to communication with our stakeholders and them not being as concerned with cost since the IMUs being used had already been purchased. Out of the component options listed, the XSens Dots had the lowest cost.

Latency
The latency of the IMUs has to deal with the response time between the sensor tracking the data in the physical realm and being able to output it in the digital. For our device, we want to provide real time feedback, meaning that we need to have the lowest latency possible within our other restrictions. For this reason, the latency category was given a 3 weight, however each IMU listed a latency of 30 ms, meaning that when came time for our final decision between the three selected options, each one received the same score for this category.

Size
The physical size of the device is something to consider because these IMUs must be worn by the research participant. Therefore, a smaller device size is preferred, and the dimensions correspond to one of the IMUs in the set. Out of all 3, the XSens Dots once again were the smallest.

Sample Rate
The sample rate deals with how frequently the data is collected during use by the IMUs. For this category a weight of 1 was assigned, as a larger sample rate could also mean more data fed into the logic center overloading it as well as not being as important as things like latency and range. The XSens MTw Awinda IMUs had the best latency value of the IMUs listed.

Compatible Software
One primary concern for our team dealt with the lack of knowledge when it comes to working with programming and coding languages to be used with a complex device like the one we are trying to build. That is why we wanted to look deeper into the compatible software that either comes with or is available to use for each IMU. For this category, the types of software that are either mentioned in developer documentation or through searches are shown. For this category, a weight of 2 was given to show that it had some importance, especially as if we were able to choose a device with software or programming that was already familiar, we could make a device on our timeline a lot easier.

Mass
The mass category is essential in evaluating as we do not want to add too much weight to our device system by way of the IMUs. Specifications for the given mass of the each IMU are listed, and the category was given a weight of 1, as adding more weight for better sensing capabilities or longer battery life were seen as valid tradeoffs, with the mass of the IMUs seen as something that could be sacrificed and would not affect other requirements and specifications for the device developed by our team. The XSens Dots had the smallest mass.

Internal Storage
Internal storage capabilities of each IMU is important as it provides a record for the researcher of the gait pattern of a participant even if wireless modes of doing so have problems. However, the internal storage was given a weight of 1 due to the primary focus of this device being an ability to provide real time vibrotactile feedback. The APDM Opal IMUs had the best internal storage by a wide margin, containing 8 Gb of storage on the IMUs.

Data Streaming
The category that was the most important for our device was the data streaming capabilities. If the data cannot be streamed from the IMUs to a logic center for processing into feedback then our device misses the most important requirement. That is why this data streaming category was given a weight of 3, and each device was categorized on how it could stream the data that it collected during a trial. The APDM Opals had the highest score, as they are more open source in their ability to stream data from the IMU to the logic center. The XSens Dots were given a value of 0, as they have primarily been used with phone applications in the past to track and show the data in real time. However, of the three devices shown, only those two have available methods of connecting and streaming data wirelessly from the IMU.

Dynamic Accuracy
The dynamic accuracy of the IMUs deals with how accurate the values reported by the IMU are. This category was given a weight of 2, as we want to accurately track and monitor the gait patterns of participants with the IMUs selected. Accurate data into our logic center is crucial as we want the feedback given to participants to be accurate to what the researcher is looking for from the study. Of the three IMUs, the XSens MTw Awinda IMUs had the best dynamic accuracy and were assigned a value of 1. However, each of the IMUs selected had very similar values.

Range
The range of the device categorizes how far the device can be from the logic center as provided through documentation from suppliers of the IMUs. The values shown are in meters, and show how far away the IMU can still connect with the researcher UI side of the device to communicate with the logic center as well. This category was assigned a weight of 3, as a primary requirement from stakeholders was to be wireless and in conversations the idea was to use a long hallway to create a walking path for a research participant. So this category was assigned the largest weight on our scale. Of the three IMUs, the XSens Dots has the largest range of 40 meters. Having a large range could provide researchers with a better opportunity, and less restrictions and test procedures that they would pursue when working with those dealing with gait disorders.

IMU Selection Results
After going through our IMU component selection analysis, our team decided to proceed with using the XSens Dots. The dots received a total score of 7, which was 6 points higher than the next highest score of 1 by the APDM Opal sensors. The XSens provide us with major specifications in terms of their range, 40 meters, latency, 30 ms, as well as their usability and wide range of available resources already produced, like applications for phones, windows and Mac OS. Therefore, after going through our component selection process for the IMUs, we decided to move forward using the XSens Dots for our device.

Logic Center Selection
Picking a logic center that can handle a lot of input data and is capable of streaming are two of many factors that our team considered when creating a scheme for the selection of the logic center. The logic

center serves as the central part of the device design that will take the input data from the IMUs and feed it to the tactors to create the patterns and tactor activate desired by the researcher setting up the participant trails. The logic center must be able to process incoming data from 5 IMUs, which can produce large data files that have comprehensive motion tracking to be used for providing correct vibrotactile feedback. In Table 6, the categories and specifications are detailed for our logic center selection method.

Table 6. Logic center selection pugh chart. The weights are assigned on a 1-3 scale, with 3 being most important and 1 meaning least important. The Raspberry Pi 4 received the highest total score of the three logic centers ranked.

Logic Controller		Arduino Uno		Raspberry Pi 4		Particle Photon 2	
Categories	Weight	Value	Specification	Value	Specification	Value	Specification
Cost	1	0	$23	**-1**	$120	1	$20
Size	1	0	68.6 x 53.4 mm	**-1**	56 x 85 mm	1	36.58 x 20.32 mm
Ram	3	-1	32 Kb	**1**	up to 8GB	0	128 Kb
On-Board Bluetooth Capabilities	2	-1	None	**1**	Bluetooth 5.0	-1	None
Clock Speed	3	-1	16 MHz	**1**	1.5 GHz	0	120 MHz
Language	2	1	Arduino C++	**0**	Python, C, C++	1	C++
Total		-6		**10**		2	

Cost
The cost of each device needs to be considered as it can be used as a determining factor in the design of a final product. That is why it was considered, but given a weight of 1. The device with the lowest cost was the Particle Photon Board, retailing at the cheapest price of $20.

Size
The size of the logic controller also plays a role in the selection process as our design incorporates the idea of having the logic center carried inside of a pocket of a vest. Therefore, the logic center must be a smaller size. The three logic centers were scored, and the weight for the category was a 1 as the size isn't something that is crucial to the overall design of our device. The Particle Photon 2 logic center received the highest score as it had the smallest area.

Ram
The on board ram available to each logic center helps determine the ability for the logic center to process the input data. More ram means more power to process data, which is essential in our design as a lot of input data is needed from the five IMUs incorporated in our design. Having more ram allows us to transfer more of the data at a quicker rate and avoid any bottleknecking that may occur from having too much

data streaming. For this reason, we gave this category a weight of 3. Of the logic centers we examined, the Raspberry Pi 4 scored the highest value with 8 Gb of ram.

On-Board Bluetooth Capabilities
The IMUs chosen by our group, the XSens Dots, use bluetooth to communicate with other wireless devices and to transfer data in real time. Therefore, choosing a logic center that already has built in bluetooth wireless connectivity would be very beneficial. For those reasons, a weight of 2 was assigned to this category. Of our logic centers charted, only the Raspberry Pi 4 had bluetooth on board capabilities.

Clock Speed
Much like ram, clock speed affects how fast and how much information can be received by the logic center. A larger value for the clock speed means more information can be processed at a time and is much more desirable for our application. A weight of 3 was assigned to this category as being able to process the data at a high rate is very important when trying to provide real time feedback to a participant wearing the device. For this reason, the Raspberry Pi 4 was once again the best option with a 1.5 GHz clock speed.

Language
Programming language was identified as a potential issue with creating this device, as internally our team has a lack of experience and knowledge on computer programming. Selecting a logic center that has a way to code in C++ was deemed as beneficial to our team, and the category as a whole received a 2 on our weight scale. Both the Particle Photon 2 and Arduino Uno boards are C++ compatible and have simple coding languages so they were assigned a value of 1 for the category, while the Raspberry Pi 4 received a zero due to the many complex languages that it can use and the teams unfamiliarity with the logic center’s setup.

Logic Center Selection Results
After going through this analysis, our team found that the Raspberry Pi 4 was the most beneficial component to select for our logic center. The large virtual memory in the form of onboard ram and a much greater clock speed than either of the other two options proved to be the most important distinguishers for the Raspberry Pi 4. Also, as the device has bluetooth capabilities built in, we believe that it provides our team with the best solution to our wireless problem, as no other components need to be researched and combined into the system, alleviating any other potential problems with hardware compatibility. For these reasons, our group has decided to use the Raspberry Pi 4 to construct our vibrotactile feedback device.

Tactor Selection
Selecting the right tactors for use with our device is an essential component to the success of the vibrotactile feedback to be given to the participant wearing the device. These tactors must also be safe for use as they can come in close contact, and provide feedback that can be felt by a participant using the device. The tactors were evaluated based on the categories determined by the team, and shown in Table 7.

Table 7. Selection pugh chart used for selection of the coin tactor motors. Each motor was ranked based on the given specification in relation to each other, with weights being assigned on a scale of 1-3, with 3 being the most important and 1 being the least.

Tactors		INEED C1034BE03L27		INEED C0820BE03L27		Hxchen DC3V	
Categories	Weight	Value	Specification	Value	Specification	Value	Specification
Rated Min. rpm	3	1	10000 rpm	1	9000 rpm	0	12000 rpm
Operating Voltage	2	0	2.7 - 3.6 V	1	2.5-3 V	-1	3 V
Diameter	2	0	10 mm	1	8 mm	0	10 mm
Cost Per Motor	1	0	$2.65	-1	$2.80	1	$0.89
Total		3		7		-1	

Rated Min. rpm
The minimum rpm that the motor is capable of is based on the rated voltage for the motor. We want a value that is lower, giving us a better range to be used for the researcher to use as an output during use of the device. Having this built in adjustability also allows our group to experiment and find different methods to wire the tactors. For these reasons, the category was given a weight of 3, with the two motors by INEED having a value of 1.

Operating Voltage
The operating voltage was another category that was considered as being able to operate at a lower voltage means that less overall power will need to be supplied to the device. For this reason the category was given a weight of 2, as it influences other aspects of the design. The INEED C0820BE03L27 coin motor received a value of 1 as it had the lowest possible operating voltage out of all of the motors compared.

Diameter
The diameter of each coin motor is another aspect of design that plays a crucial role in further design modifications moving forward. This primarily has to do with the arm band sizes, as well as how the implicit array will be arranged on the torso of the vest of the device. For this reason, the category was given a weight of 2. The INEED C0820BE03L27 coin motor once again has a value of 1, as it has the smallest diameter.

Cost Per Motor
Finally, the cost was used as a final category to compare between the motors selected. Again, cost is not a primary concern, but something that was considered, thus providing the rationale for assigning the category a weight of 1. The cheapest motor, assigned a value of 1, was the Hxchen DC3V, retailing at $0.89.

Tactor Selection Results
After completing the tactor selection analysis, our team determined that the INEED C0820BE03L27 motor was the best choice, receiving a total score of 7 which was 4 points greater than the other INEED motor

that was analyzed. This gap was determined to be sufficient enough to show that the INEED C0820BE03L27 coin motor was the best choice. The primary distinguishing was the size, as being 2 mm smaller in diameter allows for a tighter in overall space vibrotactile implicit array to be constructed on the vest of the device, while also ensuring that the motors will fit on the arm and leg straps to be used in fastening the tactors to the participant during research. For these reasons, after completing the component selection analysis for the tactors, the decision was made to proceed with the INEED C0820BE03L27 coin motors.

Final Takeaways

After completing the component selection analysis, our team has solidified the components to be used for the final vibrotactile feedback device that will be constructed. These components are all essential to making sure that we can provide a device that not only gives vibrotactile feedback to a participant, but also will give a researcher valuable information and data to be used to determine the best ways to provide this feedback and help train people with gait disorders to improve their mobility. Furthermore, the components selected all have the ability to work together in tandem, and the priority for the team moving forward is to work on these connections and establish them as soon as possible to ensure the completion of a successful device by the stakeholders deadline at the end of the winter 2022 semester.

Engineering Analysis - Live Streaming IMU

As outlined in our FMEA analysis the live streaming aspect of our design is the most critical and highest priority. If there is no established way of being able to see and process the data in real-time we are unable to provide any sort of feedback to the participant using the device. There are many different ways to approach getting the IMUs to stream data and this analysis will outline the different approaches taken and the logic behind them.

Raspberry Pi to Xsens Server

The first tested method to get our raspberry pi to communicate with the Xsens server. This route was chosen first because of the clear information about how to interact between the Xsens dots and the raspberry pi. This method was also used by the previous team which seemed like a good place to start. This method required us to initialize the raspberry pi through various commands to be able to start and access the server. Ther server is where we actually are able to interact with the dots. This means different modes, connecting and disconnecting the dots, and logging the data. This then processes and begins to fill a CSV file on the raspberry pi. This led us to believe that if there was a way to interact with the CSV file as it's populating and see if this can be real-time enough. We began to write a python script for the RPI to try and keep reading the last line but were unsuccessful due to a lack of knowledge regarding python syntax. The positive of this method was that it allowed us to view the file and get a better understanding of the actual data that is being outputted. Another observation noticed was that all five dots would not connect and collect data. At any point, only 1-3 would collect data and connect.

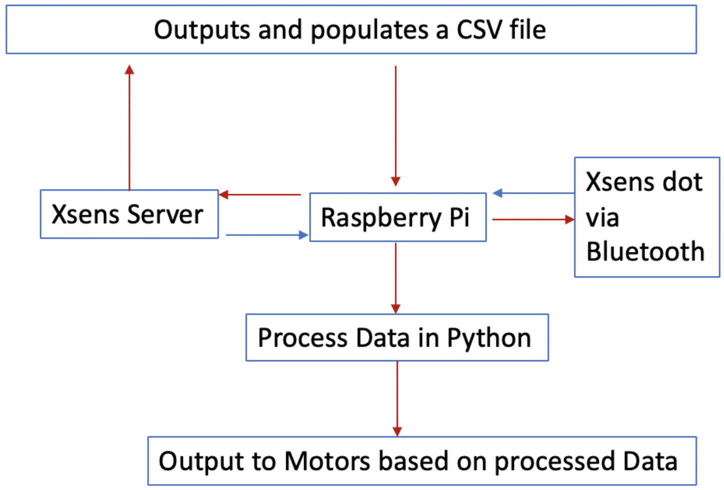


Figure 31.

Python Live Animation Script

This led to new creative ways to test ways of plotting and storing real-time data. A script was developed that used python libraries such as pandas,matplotlib, and funcanimation which allowed for a figure to be constantly plotted in real-time if a CSV is being written. On the PC with sample data, we were able to run the first walking test with one IMU to make sure the file was able to be plotted even if it wasn't real-time. IN figure 32 shows the accelerations and positions plotted for one IMU but not live. This led us to begin running this pythons script developed on the PC to the RPI and see if the RPI can plot as the CSV is getting filed from the server. The team ran into troubles getting these python libraries on the RPI but eventually were able to but the issue became the CSV file that was being populated no longer was being written to. The file would stay blank until we hit stop. This means it was still recording data but no longer in real-time which is not satisfactory.

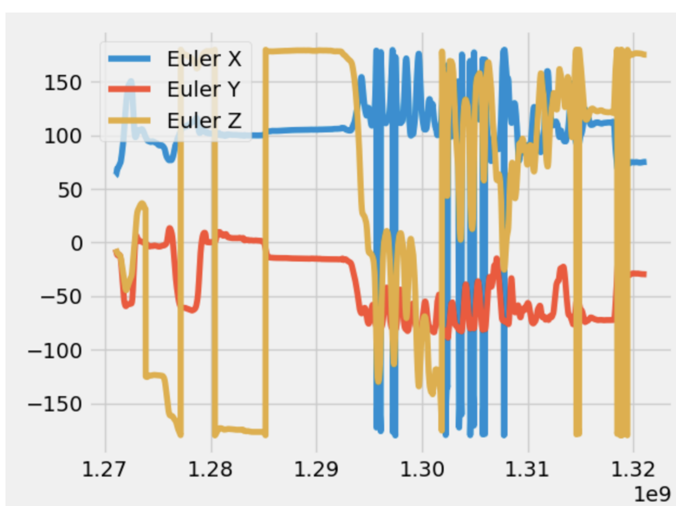


Figure 32.

PC/MAC to Xsens Server

Since on the RPI it was not populating the file this led us to try and use the same support instructions off of GITHUB for it to work in the same way except through a PC or Mac. This could allow us to prove if the script was functional or not if it would populate on a computer. Unfortunately, after trying between two windows laptops and one mac laptop neither of the setups was successful.

Python

This made the group take a different avenue by trying to avoid connecting to the server and directly into python. There was information found on running several scripts to initialize and find the dots. There was little documentation and many errors found while trying to run it which led us to try new things but potentially come back to this method for further analysis.

C++, Javascript

Other methods that avoided the XSens Dot server included C++ and Javascript. The C++ method included using a C++ IDE to access the computer's bluetooth capability to communicate with the IMUs. From there, data collected by the IMUs could be used with the correct logic to output to the GPIO pins of the Raspberry Pi (which output to the motors). This data flow, however, was not clearly documented or found in the C++ files. This led to many errors while running the main script that were very difficult to debug. Similar problems were encountered while running the Javascript-centered files (which involved several MATLAB scripts supporting the central Javascript file) with the addition of not being able to access the Javascript file at the time. After a considerable amount of time attempting to troubleshoot these methods, the team decided that different approaches may be better and that the C++ and Javascript methods were best left as potential back-up solutions.

MATLAB

The MATLAB script successfully worked by directly connecting the dots to Matlab via Bluetooth low energy commands. In figure 33 the block diagram shows the simplified path of communication between the whole system. The base script was found on Github which was very helpful in understanding how to get the sensors initialized and converted into usable data. This is combined with the service manual has made the Matlab option our most successful yet. It allows for direct connection with no server complication, one script to handle the plotting and connecting, and most importantly shows and stores the data and plots in real-time in the Matlab plot window. Figure 34 is an example of what the real-time plot may look like.

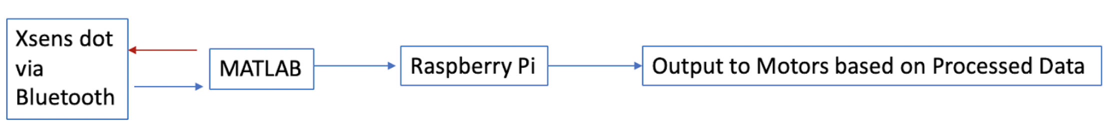


Figure 33

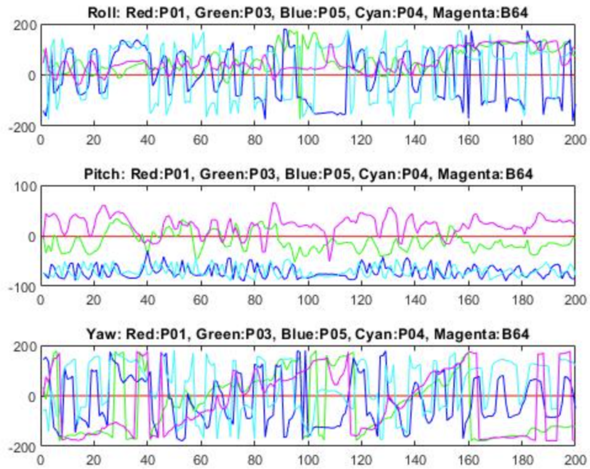


FIGURE 34. Sample Plot Window

Engineering Analysis - Tactor Activation

Tactor activation is an important area of analysis in our project as how fast the tactors activate, how easy it is to feel the vibrations, and how reliable the tactors are, all determine how effective our feedback to participants with gait disorders will be. Our team completed several tests to determine the effectiveness of our chosen tactors (INEED Coin Motor - C0820BE03L27) to ensure that quality feedback was being given to participants.

Tactor Activation Speed / Latency

The tactors we used had to have a fast activation speed else we would run the risk of not giving real time feedback to our participants. There are several variables that determine the latency of the tactors. The Xsens Dot sensors themselves have some latency in collecting the data and converting the data to numbers. This data is then wirelessly streamed to MATLAB, in which a code runs that converts the data from the Xsens Dots to a more usable form written plainly in pitch, roll, and yaw. This code runs continuously and updates the pitch, roll, and yaw array as fast as it can receive and process the data. This data is then sent wirelessly to a Raspberry Pi via a Wifi connection. The raspberry Pi then sends a signal through wires attached to GPIO pins on the Pi to the tactors. The tactors receive this initial signal, but have some response time in which they ramp up to a full vibration that will be felt by the participant.

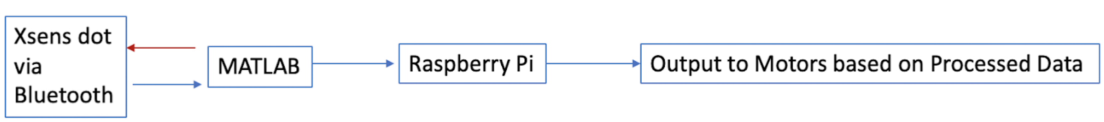


Figure 35: Improved flow chart using MATLAB and Xsens Dot directly communicating with each other. There are delay times within and between all locations on the flow chart.

It's clear there are several variables that can affect this response time from sensors collecting gait information, to the tactors vibrating to show a deviation from expected gait. Because of the difficulty in calculating a response time theoretically (especially since these variables could change from one Wifi network or computer to another) we decided to run an empirical test on the MWireless network to determine the quality of the feedback. This is an engineering analysis still in progress, the group hasn't found an exact time between exceeding a sensor threshold and activating a tactor, but based on a usability analysis by our group members we all felt that the tactor activation speed was nearly real time and we think a conservative estimate for feedback latency would be 0.5 seconds, and likely less than that.

One note to consider with tactor feedback is that the amount of data input to MATLAB has a significant impact on the performance of the feedback at this time. During testing we observed that sending pitch, roll, and yaw data from all five Xsens Dots resulted in a very slow processing of data by MATLAB. While using Caleb's computer, the processing speed of the data was about one update every two seconds, far too slow for real time feedback. While using Joe's computer the processing speed of the data was much faster (less than one second per update), but still too slow to be considered real time. It may be the case that a fast computer needs to be used to run multiple data streams through MATLAB with multiple "rules" for feedback at once. The sample tactor activation code in the Appendix shows how a single IMU can control a single tactor. This code runs very quickly on Joe's computer.

Strength of Tactor Vibration

The stretch of tactor vibration is another variable that is critical to gait feedback. Because participants will be walking while feedback is being given to them it's important that the strength of the feedback signal is powerful enough for them to feel. During concept generation earlier in the semester the group considered that they sometimes didn't notice their phone vibrating in a pocket while walking, but always noticed if their phone had gone off while they were still. Because of this phenomenon of missing weak vibrations due to body movement, we wanted to make sure that our tactors can deliver vibrations that are powerful enough to be felt while walking. Our group aimed to realize this goal through two different methods: first making sure our tactors vibration frequency was well within the human sensory limits, and also making sure we have firm contact between the tactors and the body of the participant.

Based on the engineering specifications for the wearable device, the peak human vibration sensory range is from 60-300 hz. The tactors we selected vibrate at a speed of 10000 rpm, which converts to 166 hz, so these tactors are within the range of high sensitivity to vibration.

The second way to ensure participants feel the vibrations created by these tactors is through the wearable device having good contact with the skin. On the head, arms, and legs, velcro straps will be used that can be tightened as necessary to keep the tactor in contact with the participant's skin. The tactors we choose have been designed with wearable devices in mind and come with a 2mm thickness. This helps participants to feel comfortable with the tactors up against their skin, because if the tactors were much thicker the participant could feel discomfort from a large bump pressed to their skin. These thinner tactors should be more comfortable to wear and less intrusive on a participant's natural gait.

We received the vest that we ordered on April 6th, so we have not had the ability to test and ensure strong contact between the implicit array on the participant's torso and the tactors that will be stuck onto a velcro pad that is sewn onto the inside of the vest. However, the team did prepare for the contact between the vest and the participant's body by purchasing a vest that has tightening straps around the waist. This should make sure we can tighten the vest to provide good tactor contact to the skin for people of various sizes.

Tactor Activation - Raspberry Pi Interfacing

An important part of the team's work in confirming that these tactors could be used successfully with the Raspberry Pi and MATLAB was to test the ability of the tactors to work with the Raspberry Pi. The Raspberry Pi runs its GPIO pins at 3.3 V and has a maximum limit of 16 mA per GPIO pin. However, the rail that supplies current to the GPIOs has a maximum current of 50 mA for the entire circuit. In a worst case scenario for the Raspberry Pi, all 16 tactors will be activated at the same time, requiring a maximum current of only 3 mA per tactor to ensure the rail powering the pins doesn't overheat. A 3 mA current with the 3 V operating voltage of the tactors will likely not be enough power to cause the tactors to vibrate at a high enough intensity to be felt by participants. A better worst case situation can be found by assuming that implicit feedback and explicit feedback will never occur at the same time. With this assumption the maximum number of tactors that can be one at one time is the 9 implicit tactors. However, this problem still persists because 9 tactors requires that only 5 mA is used per GPIO pin and therefore only 5 mA per tactor.

To get around this problem the team has realized the need for using relays and transistors to control a high powered circuit with a low powered control board. We have access to these components from a previous ME 450 team and will be finalizing our connections on a permanent solder breadboard so the tactor and Raspberry Pi interface is lasting.

Engineering Analysis - Battery

In order to ensure the device is fully functional there needs to be enough power supplied to all the tactors and the raspberry pi. The 5 IMUs are all individually powered so are not part of the calculation. The raspberry pi 4 8GB under a 400% CPU load which is a worst-case scenario will use 1280mA. The 17 tactors all vibrating at 12,000 rpm would use 1360mA. All of the motors would not be vibrating at full capacity but this allows for a safer component selection. This means the battery chosen must be at least 2640mah in order to run the device for an hour. The team decided to go with a 10,000mah battery instead to allow for more than an hour of use which allows for fewer charges for the researcher.

Design Verification Results

Design verification is required to ensure that the concept our group chose and developed has correctly met the requirements and specifications listed out by us and our stakeholders in the problem definition phase of the design process. To show our design verification process, we have created a verification table where requirements and specifications are listed and verification processes are shown. This table is shown below. Green highlight indicates that the verification plan is complete and successful while orange highlights indicate that the verification plan is not yet complete. Further explanation will be provided below the table.

Requirement	Specifications	Verification Plan/Tests
Reconfigurable Wearable Device	1. The device must accommodate a head circumference of 50-62.7cm 2. The device must accommodate a wrist circumference of 12.7-20.4cm	Component selection analysis - head straps were chosen to be flexible headbands, this allows for different head sizes to fit and an adjustable tactor will allow for consistent tactor

	3. The device must accommodate an ankle circumference of 15.9-26.7cm 4. The device must accommodate a waist depth of 13-29.9cm	positioning. Component selection analysis - straps selected with length of 30 cm, long enough to attach to both arms and legs of participant. Component selection analysis - vest chosen that can be worn by multiple body types, vest has tightening straps on side to provide snugness for all body shapes.
Comfortable for Subject/Does Not Affect Gait	1. Participant worn devices < 5.5 kg 2. Devices on extremities < 1.5 kg 3. Device has no common allergens - Formaldehyde resins that can cause rashes on participants 4. Wires secured to the body without adhesives on skin 5. Wires < 2 cm from body 6. Device can be put on participant in < 2 mins	Weight analysis - not completed for full device. Weight analysis - devices on extremities (IMUs and tactors) will be well under 1.5 kg. Component selection analysis - The device uses common materials found in clothing and velcro material used in other wearable clothing applications. Full device trial wear - tests to confirm that wires stay close to the body without adhesives on skin, and that the device can be put on in a reasonable amount of time have not yet been completed because the team only recently received the vest.
Wireless Connection to User Interface	1. Range of 0-(-60dbm) indicating good signal strength 2. Range of 13 meters from the computer or phone operating the sensors 3. 10000 mAh battery to power the device for about 7 hours of use	MATLAB trial runs, IMU analysis - multiple trials were done to confirm that the IMUs can communicate with MATLAB from over 13 meters away. The device can run wirelessly with no problems. Battery analysis - the battery size was chosen by a theoretical analysis that shows the consumption of the device and picks a battery size based on the consumption.
Explicit Vibrotactile Feedback	1. Haptic feedback in sensory range of participants (vibrating motors capable of 60 to 300 Hz) 2. Feedback to head, left arm, torso, and both legs	Tactor activation tests/component selection analysis - tactors were activated by communicating from MATLAB to a Raspberry Pi wirelessly. These tactors vibrate at a frequency of 166 hz per their datasheets. Tactor feedback test - we can preliminarily test feedback to all locations of the body by attaching 5 tactors to the Raspberry Pi and ensuring that all tactors can operate simultaneously. A more certain verification test can be run when the full device is built and tested as an entire unit.

Implicit Vibrotactile Feedback	1. Haptic array of 3x3 to 5x5 feedback points 2. Minimum 60 mm between feedback pointsfor two point discrimination 3. Haptic feedback in sensory range of participants (vibrating motors capable of 60 to 300 Hz)	Component selection analysis - a 3x3 array was chosen based on simplicity while still providing the necessary patterns. Vest construction analysis - since the team only recently obtained the vest to be used in implicit feedback, we have not attached the tactors to the inside of the vest, however we are certain that it is possible to create this array with 60 mm spacing when we build the device. Tactor activation tests/component selection analysis - tactors were activated by communicating from MATLAB to a Raspberry Pi wirelessly. These tactors vibrate at a frequency of 166 hz per their datasheets.
Sensors capture body kinematics	1. Velocities up to 10 m/s 2. Accelerations up to 70 m/s^2 3. Angular velocities up to 500 degrees/s 4. Angular accelerations up to 10000 $degrees/s^2$ 5. 60-120hz sensor sampling rate 6. At least: 1 sensor on head, 1 sensor on left arm, 1 sensor on torso, 1 sensor on each leg	Component selection analysis - the chosen Xsens Dot IMUs are specifically designed for use collecting human feedback. They are rated for 2000 degrees per second and 16 g's of acceleration which meets our data collection needs. Component selection analysis - the Xsens Dots can output at 60 hz when operating in real-time feedback mode and can collect up to 120 hz when recording data. Component selection analysis - five Xsens Dots are available for use to our group, enough to meet the engineering specifications.
Electrical System is Safe for Participants	1. Participant leakage current does not exceed 100 μA 2. Ground resistance does not exceed 500 mΩ	Leakage current tests - tests have not been performed to ensure the leakage current is low enough. Leakage current testing tools are available for purchase, however testing for leakage current may be out of the scope of this class because of time constraints. Further discussion between the group and stakeholders can determine if a leakage current test is necessary to verify the design.
Lasting	1. Wire connections are soldered and wire connector clips are used to attach and detach tactors 2. The sensor attachment harness can be washed without damage	Component selection analysis - wire connecter clamps were purchased to ensure that tactors could be removed from the device easily. A solderable breadboard has been purchased, but has not yet arrived. We can verify our design is functional by testing the full device when it is completely put together in the near future. Component selection analysis - velcro attachments were used at all tactor connection points in the wearable device to ensure that all tactors could be removed from the device and the device washed.

Configurable User Interface	1. Ability for researcher to define rules to create control signals for feedback 2. Input vibrating feedback intensity, pattern, and sensor thresholds for vibration in < 2 mins / (2 minutes maximum downtime between participant trials) 3. Input subject ID, age, weight, disorder, trial number, date and time < 5 mins / (5 minutes maximum setup time for each participant) 4. Ability to export data into csv format	MATLAB feedback testing - MATLAB testing confirmed that tactors could be controlled based on sensor input from the Xsens Dots and logic rules in a MATLAB script. MATLAB useability testing - a useability test needs to be done to confirm that thresholds can be updated within 2 minutes. It's likely that our device will FAIL this engineering specification due to time constraints and unfamiliarity with creating user interfaces. Interface testing - testing has not been done to confirm that participant information can be quickly filled out. We will likely FAIL to achieve this specification because designing a user interface was not achieved by the team in this semester. Another document will need to be used to track participant information separate from the MATLAB script to run the feedback. MATLAB interface testing - a test that the team needs to complete is ensuring that feedback data can be written into a CSV after use. This should be possible based on functions available in MATLAB.
Functional Software Language	1. MATLAB, Python, C software 2. Can stream data to the user software for troubleshooting/ calibration of device	Language usability testing - testing was completed by the team to ensure that we used a language that was subjectively easy to use by our group members. Our stakeholder Safa Jabri indicated she was comfortable working with MATLAB. Our device communicates using MATLAB only so this specification has been verified. MATLAB IMU testing - the team conducted several tests to ensure that data could stream from IMUs to MATLAB. This was confirmed by a test that plotted pitch, roll, and yaw output based on the movements of a group member with the IMUs attached.
Portable	1. Researcher device weighs < 2.5 kg 2. Researcher device is wireless from wearable device	Component selection testing - the group selected a laptop to be the researcher interface for testing. Most laptops weigh under 2.5 kg so this specification is verified. MATLAB streaming analysis - a plot was created in MATLAB of a group members walking pattern as they walked around hallways in the vicinity of the computer. The plots were able to update wirelessly and at range.

Failed Verification / Tests to do

A weight test has not been done for the entire wearable device system. The team has only recently received all the components necessary to do this test. Once we assemble the final device we can weigh our device on a scale to determine if the weight of the device is under 5.5 kg.

Because all components have only recently been obtained, we have not had the opportunity to test how far the wires will fall from the body during usage. We should be able to attach all wires to the body without needing to use tape or other adhesives on skin. Finally, we can perform usability testing within the group to determine how easy it is to put on and take off the device.

Feedback to all body parts has not been tested because we do not have an assembled device at this time. Once we begin to put all of our components together we can confirm we meet the engineering specification to deliver feedback to all body parts.

Without a vest, we were unable to attach tactors to the vest and confirm two-point discrimination distances. However, we are confident that there is space on the vest to achieve these 60 mm spacings between tactors.

Leakage current tests might be outside of the scope of ME 450. Because our device will not be used on participants before the end of the semester and due to time constraints to finish our device, it is unlikely we will perform these current tests before the end of the semester. We are planning to talk to our sponsors, Dr. Sienko and Safa Jabri, to discuss whether leakage current tests are required to complete verification for our device.

Soldering wire connections should be possible due to the breadboard we purchased, however it will be hard to know whether the device works properly with the solders until we complete the wearable device.

The researcher user interface may not be completed this semester due to time constraints. We are planning on using MATLAB as a user interface and writing our code in a way where it's easy to change thresholds. Creating a full fledged user interface that can communicate with MATLAB separately and input participant information before trials could be out of scope for our group.

Validation Plan

Validating our design is an important step to make sure that we have provided all the necessary information and instructions to be used with our design. While verification focused more on hard specifications and making sure requirements were met, validation deals with the actual use of the device as well as our stakeholders input on our design. For these reasons, the validation process that we propose has two distinct steps, the first being what can be accomplished before the end of the semester when the device must be handed off to the stakeholders, and what validation process should come after that. Our two part validation process is thus broken up in this section, first looking at what our group will try to accomplish, and then what it will not be able to accomplish due to time constraints.

ME450 Validation Plan

With the time constraints of the current semester and class, our ME450 validation plan has to center around what tests of the device we can actually do. This starts by using the device as a team, where one member will act as a researcher manipulating the feedback settings and trial setups, while another member will work as a research participant and wear the device. Using this validation plan allows our team to test all the systems together while also being able to first hand experience the sensations of the vibrotactile feedback. Getting this first hand feedback is crucial, as any engineer should be able to willingly use the things that create. Therefore, the first step to our validation plan is to work within the team, wearing the device firsthand and having one member act as a researcher.

The second step to our validation plan for the ME450 course is to test the device with our primary stakeholder and other graduate students that are associated with the Sienko Research Group. Using this step allows our team to receive feedback from a group of individuals who have more experience working with similar devices, meaning they can give feedback on parts of the device that may be of concern for participants wearing the device during research, or from the researcher perspective some of the changes that need to be made from the UI side of the device. Our group plans to have a questionnaire that can be used, where the individuals wearing the device as well as the individual acting as the researcher can both answer questions pertaining to their role. For example, the researcher would be asked about the ease of use for the UI in changing research parameters, while the person acting as a participant would be asked questions about how comfortable the device was as well as how well they could feel the feedback patterns and explicit feedback in different locations on the body.

Our team of course does have some worries about the effectiveness of this validation plan. The first being the time constraint that we are on. Making sure that we can at least get through the first step of this validation plan is the most important, as once the device is handed off to the Sienko Research Group they may be able to go through the second step of our validation plan. The second concern deals with the effectiveness of our own testing as part of the first step. Of course our group does not have much experience working with individuals with gait disorders and devices used in the research setting. With this in mind, making sure that the device functions as part of step one will be the primary focus, with the secondary focus being how the input data from the IMUs affects the feedback patterns.

Long Term Validation Plan

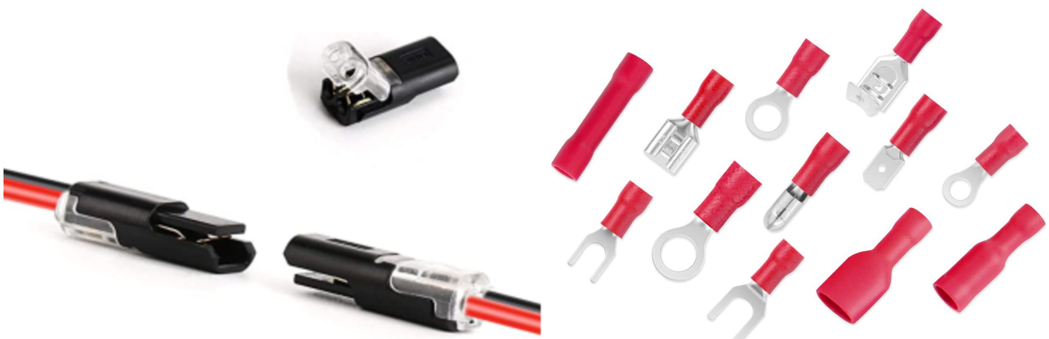
In the long term, validation of the device needs to also involve actual participants with gait disorders. Testing a device like this that is supposed to help a certain population of people must also include that population of people. However, there are many clearances and approvals that must be made by the University of Michigan before our device can be used on research participants. These approvals take time and further explanations, experimentation with the device, as well as long processes to get approval. Seeking IRB approval from the University of Michigan can be a long process that must be completed before doing any testing with human subjects in research. For this reason, using the device on people outside of our group or individual that are part of the Sienko Research Group could not be done before the end of the semester, but is something that would be needed to have a full validation of our design, as the research participants hold some sway as a secondary stakeholder in the design and implementation of our device.

Lessons Learned

Throughout our current design process, we have failed and learned several times in terms of testing and component selection. Much of these failures resulted from lack of experience and lack of precedence (no previous, successful, and documented attempts by others). These learning experiences resulted in fundamental changes to the function of our final chosen design as well as component selection in multiple aspects.

Wiring Connectors

The first and simplest failure came from the plastic wiring connectors. The intended application of this component was to provide the user the option to physically disconnect motors and reattach them whenever needed. The connectors would attach to wiring on one side and then connect to another connector at the other (creating the easily removable connection). Upon receiving these components, it was apparent that the connection between the wire and the connector was very weak and the connector-connector connection was very strong. Since our design requires strong connections on both sides of the connector to greatly reduce the possibility of losing electrical connections during trials, it was decided that a new wiring connector should fulfill this purpose. The new connectors include a crimpable rubber side (creating the permanent connection) and a variety of female and male components that create reliable, non-permanent connections. These connectors are shown below in figures 36 and 37.



Figures 36 and 37. The original wire connectors (left) only created strong connections between connectors. The new wire connectors (right) are crimped at the rubber (red) side and attached to a double female connector at the other side (in which the second female side is crimped to another wire).

Upon inspection of the original wire connectors, the team recognizes that engineering analysis is not always complex simulation and calculation. Sometimes, analysis can just be buying samples of a component to verify that the component functions as expected, especially for components that lack reputation (such as the original wire connectors). If our team had identified this earlier, purchasing for these components may have been done with the intent to test and may have been done much earlier. The team had identified components to order early, but mainly for the purpose of having finalized components readily available for use.

Live-streaming Data

As seen in our engineering analysis, the XSens Dot Server was the starting point for which the function of our project was to build upon. On several XSens Dot manuals and websites, the capability of the server to connect to the XSens Dot IMUs and provide real-time streaming was advertised and discussed in brief. However, it is evident by the results of our analysis that this is not completely true, and our team very quickly learned that the server is not suited (as is) to the needs of our stakeholders and design. This prompted research into several options that eventually led to successful live-streaming of XSens Dot IMU data to MATLAB which involved long hours of trial and error with several online resources. Throughout this period of failure, it was very easy for the team to lose trust in any given option upon successive failures, but through persistent testing and deep analytical thinking, breakthroughs were made. Moving forward, our team fully acknowledges the idea that each failure is a step closer to success and that there is always something to be learned from failure. This failure learning process, however, takes time. Our team lost plenty of time to the process that could have gone to other aspects of our solution, such as the mechanical and electrical subsystems (mainly involving their construction and testing). A design recommendation from our team with respect to troubleshooting and exploring any software design is to give as much time as possible to the process. If our team had known this before, we would have begun software testing much sooner.

“Shopping Cart” Analysis

The team had identified specific coin tactors, IMUs, and a logic controller early in the design process for use in the final design. This was done through “shopping cart analysis” in which a component is identified for purchase after all of the chosen design specifications attributed to that component type has been met (eg. a small motor that can vibrate at a certain frequency is needed, so a small motor that can vibrate at a certain frequency is chosen since it meets the “small” and “frequency” specifications). Our original choice of coin tactors, the Solarbotics VPM 2 motors, were identified as a finalized component until the team discovered that purchasing them involved some complications (ie. extra charges in purchasing which would have delayed their arrival). The solution to this problem was very simple since several companies can provide vibrational coin tactors. Tactors from another company were identified as an equivalent to the original tactors and were ordered without (financial) resistance. This whole process (which took about a week and a half) could have been easily avoided had the team more carefully considered the chosen vendors. One minor complication with the new choice of tactors was a large delay in delivery time (likely due to oversea shipping), but they still arrived within the current design phase. After this experience, the team understands more fully the implications of choosing the right vendors and recommends considering both the vendors themselves and their distribution locations as factors in the design process given their potential effects on the design process timeline.

Discussion

Problem Definition

The problem we addressed this semester was the need for a device that can improve the quality of life of people with gait disorders and help our sponsors, Dr. Sienko and Safa Jabri, gather data on these people with gait disorders. Our problem was framed in a way that required our group to create a feedback device to address this problem. However, if the problem was defined differently we might have come to different solutions. If our team had more time and resources to identify the problem at the beginning of the semester, we would have done more research in different areas.

An interesting area of research might be what are the effects of gait disabilities on the everyday life of individuals who have these disorders. It’s possible that while the core problem is their gait, a symptom of this problem could warrant a solution by itself. For example, if we found that the primary problem people with gait disorders face is their inability to exercise, then maybe the solution is to create an exercise platform that accommodates these individuals. Likewise, if the main problem that people with gait disorders face is instead their inability to spend time with family, then that might warrant the design of a more versatile mobility scooter to make spending time easier. To answer these questions our team would have surveyed people who have disorders like vestibular problems, Parkinsons, or complications from strokes to see what is the best way we could help them improve their lives. We could also survey hospitals and especially physical therapy centers to better understand the symptoms of these gait disorders and speak with medical professionals in the field of these disorders.

Another area of research that could have been further investigated was the specifics of how a wearable device could be used. When the design problem was handed over to us, the problem statement included a description of a vibrotactile full body device that can give feedback on gait. However, an area that our group could have researched more was what specific parts of the body needed feedback. This could have been learned by investigating more literature on gait disabilities, speaking with medical professionals, and talking to people with gait disabilities. If we learned that the main area of issue was the head not moving while walking, then maybe our device would have been better if we just focused on the head rather than the entire body. It's possible that the device we designed was the most ideal realization of a gait feedback device, but our group didn't do as much research in this area because the requirement of a full body device was given to us early in the project.

While our problem was identified as the need for a device to provide gait feedback to people with gait disorders, defining the problem differently can lead to other solutions that may have been more beneficial to people with gait disorders. One positive of the device we created is that it can also provide insights for researchers on how people with gait disorders move and respond to stimulus, which is a field of study for our sponsors. Another positive is that our device has the potential of massively improving the quality of life of people with gait disorders if it can reach a fully working form and if the feedback is useful.

Design Critique

Our final design has areas of strength and weakness. One of the strengths of our design is the ability to integrate all of our systems in a streamlined process. We use MATLAB to communicate between our Xsens Dots and our Raspberry Pi and we accomplish this in only one script. This one script can connect the Raspberry Pi wirelessly to MATLAB, search for bluetooth devices and connect with the Xsens Dots, and then start to get data from the Xsens Dots and stream the data to the Raspberry Pi where we can then input logic toward the bottom of the script to control the tactors on the patient's body. The integration of all of our systems in one script is a huge improvement over the previous ME 450 group's attempt at a similar design problem.

Another strength of our design is its ability to give near real time feedback to our participants. While this was a requirement of our design, it is hard to actually realize this requirement due to latency and communication between the parts of the system. However, after multiple tests and verification we are confident that our feedback is near real time. Real time feedback is critical in the success of our design as the ability of participants to make conclusions about their gait based on feedback is dependent on how well our feedback system works in practical application. Having real time feedback is a huge positive of our design.

A final strength of our design is its reconfigurability and usability. Our wearable device can be easily worn by the majority of people and the vest we use for the torso is adjustable at multiple points, allowing for a snug fit for multiple body types. The wrist and ankle straps we use are non-restrictive and comfortable for the most part, with small improvements in comfort coming from better designed tactor covers. Another positive from our reconfigurability is the ability to remove all tactors from their respective straps or vest. This allows the wearable parts of the device to be washed between uses and stored without worrying about damaging the feedback points.

Our device also has weaknesses and room for improvement in several areas. One weakness that can be solved with work in the near future is the permanence of our wiring connections. Because of time constraints and slow shipping of our wire connectors, we have been using a breadboard and prototyping wires for some areas of our feedback. This is a problem because transporting the breadboard could result in connections coming undone, a large inconvenience to anyone working with our device. We have already begun to solve this problem by making some more permanent connections using a solder breadboard, but this is a work in progress and will likely not be finished by the end of the semester.

Another weakness of our design is an issue with using multiple Xsens Dots at once with the MATLAB script. While our process of communication is streamlined and real time, using more than 3 of the 5 Xsens Dots at the same time can result in slow communication between MATLAB and the Raspberry Pi. The extent of the slow communication is very noticeable where communication can slow to less than one update per second, which makes our design not real time but only semi-real time. Tests that we performed while investigating this issue showed that using a faster computer can help with this problem. One group member with a fast computer was able to run the script significantly faster than another member with a slower computer. It is possible that this problem could be entirely solved by using one of the fast desktop computers in Dr. Sienko's lab where our device will be used most often. Another temporary solution is only to use 1 or 2 of the sensors at any time and give feedback to specific locations of the body instead of the entire body. Further solutions to this problem would require a further understanding on how the Xsens Dots work and how MATLAB communicates with them.

Despite our weaknesses, we believe that our device worked as we expected and intended it to. With some small improvements to the wiring and with the use of a fast computer, our device would be fully prototyped and able to be used for at least gathering some gait data and understanding how the feedback works. Verifying the device for use with people with gait disorders is further down the road with this device.

If our team could go back and redo this project we would have considered the integration of systems in our design sooner. We accomplished a lot in very little time near the end of the semester, but if we had been thinking more about the systems in our design sooner, it wouldn't have been such a rush at the end of the semester. The part of our project that needs the most future work is the fixing of the sensor streaming so all sensors can work at the same time with real time feedback. As previously mentioned, we believe this problem can be solved by using a faster computer (more RAM and CPU power). Another solution could be limiting the incoming data streams per sensor. Each sensor can send up to 6 streams of data: pitch, roll, yaw, and 3 accelerations. We are currently only streaming pitch, roll, and yaw, but if only pitch was important for the head, for example, we could remove the streaming of roll and yaw from one sensor which is the equivalent of removing ⅔ of a sensor from MATLAB. This could speed up computation time.

A final area of further improvement if we could redo the project would be focusing more on integrating a user interface with our project. In its current state, a researcher, such as Safa Jabri, our sponsor, would have to go into our MATLAB script and directly change the logic in the script to change the feedback delivered to the participant. Although we have designed our script with this in mind, it would be easier if there was a user interface our sponsors could use. In the future there might be room for improvement by designing an app that can communicate with MATLAB and change variable values containing thresholds for feedback. However, the implementation of an app like this would cause our MATLAB script to be much more complicated as algorithms for multiple kinds of feedback would have to be written before the app was made.

Reflection

Contextual Factors Reflection

Early on in the design process, our team was able to identify several key contextual factors that must influence our design to ensure that we were able to provide a useful device to our stakeholders, the

Sienko Research group. This section helps reflect on those factors, how the design, and now how the device can have these influences moving forward.

Public Health, Safety and Welfare

The device that has been constructed in this report was created and designed with the known impact of gait disorders on those individuals who have them in mind. Gait disorders lead to a decreased quality of life for those who suffer from them, as they reduce their movements through changes in walking speed, arm movements, and foot angle. These changes become disruptive in the everyday lives of these individuals, creating a worse quality of life. The device we have created will be used by the Sienko Research Group to not only track the gait patterns of individuals, but also conduct studies and research into how vibrotactile feedback can help improve the symptoms of an individual's gait disorder. This will then lead to increased public health and welfare.

When speaking about the safety of the device, the safety of the person wearing the device is very important. Our team identified several components that if they were to fail could cause a hazard for the individual wearing the device. Someone with a gait disorder that wears our device in a research setting needs to know that the device will give feedback reliably to trust that feedback and provide unbiased, real results for the researcher. The safety surrounding this device was considered and continues to be the most important factor not only in its construction, but also when the device is in use.

Global Context

Globally, in creating a device that can be used by researchers through simple means, this could lead to more research in different portions of the world while again also helping those individuals around the world with rehabilitating from their gait disorders. Having a device that is easy to use for a researcher and can fit a wide range of potential research participants was considered throughout the design process.

Social and Economic Impacts

While our team did not do any form of life cycle costing with our device, it has been assumed that most of our economic cost has come from transportation of the components that were purchased to build our final design. Social impacts in relation to use of the device were considered, when thinking about restrictions on what an individual would be able to wear. The headband used is meant to accommodate those who have restrictions on head wear for any personal reasons, while also working on the device not being restrictive of the motions of an individual, and work on the comfort for the person wearing the device.

Influence of Identities

The personal identifies of each one of our group members affects the way in which we make decisions, based on our cultural, personal, and societal backgrounds. Our group, while none of us have experienced having a gait disorder, took the time to understand the impacts that these disorders have on people. Without being able to directly feel the sensations of these disorders, this research was essential in understanding part of our design problem. The other part of our problem concerns the researcher side of the trials that will be done in the future use of our device. For this, we consulted with both of our stakeholders, Dr. Kathleen Sienko and Safa Jabri, who work as part of the Sienko Research group to better understand gait disorders. Both contributed their knowledge of these gait disorders, what has and hasn’t worked in previous research, and the ways in which the device they wanted would work not only to look at the explicit factors, but also work implicitly to further their research into methods that could be used to rehabilitate and treat gait disorders. In the stakeholder analysis section, a map of stakeholders was shown, where our primary stakeholders and sponsor were located at the center of the map, indicating that they held high influence and impact roles in our design process. There were many differences over the course of the semester between what we felt our team was trying to design and what the stakeholders envisioned. These differences often found themselves in the form of what the final delivered product at the end of the semester would be. Due to the time constraints revolving around the ME450 course, and a miscommunication on the team's part of when the final due date of the project would be, the timeline was not understood fully by our stakeholders at first. Once this was addressed, communication improved to become more about what could be done to deliver the product and results in the most complete form that would be useful for the stakeholders. Overall, through having the personal identities of all team members, and our two primary stakeholders, our team felt that we were able to achieve a solution that will work for all parties involved. The only thing that could improve the device in our timeline would be validation testing with research participants who have a gait disorder. This research would allow the team to fully have 1st person perspective on the gait disorders themselves incorporated into the design, instead of second hand accounts that were obtained through research and interviews with our primary stakeholders.

Inclusion and Equity

Every design process requires input from every team member working on that particular project. Therefore, our team made sure to create a space for all of our team members to be able to freely contribute to ideation at every step of our design process. Each of our members has different skills, interests, and perspectives which all contribute to different approaches and ideas surrounding the same topics. These aspects of our identities were discussed early in the semester and gave us an idea of the true team dynamic before any project work began. This allowed us to acknowledge the value of each individual’s input. Our team also ensured that all members of the team agreed to any major decisions and that no idea or opinion was missed during any generation phase of the project.

The differences in identity of each team member also prompted the acknowledgement of challenges with respect to each member’s strengths, weaknesses, and specific circumstances. Efficient work from the team as a whole and as individuals or subteams was, therefore, possible from the beginning of the project, because of the team’s understanding of each other’s capabilities and potential limitations. Considering each other’s preferences with respect to assigned tasks also led to near seamless distribution of work among team members. Key decisions were also always made or shared with the team to ensure that each member had an opportunity to be involved in tasks outside of their own. Our team worked well overall in accommodating each other and contributing to both the team’s and each individual’s successes.

Ethics

An important part of the engineering design process is making sure that all practices contained within each step are done with design ethics in mind. Our team’s goal by the end of the semester was to eventually provide a proof-of-concept product that could either be used directly as intended or require only minor adjustments, modifications, or assembly given well-defined instruction. To provide a product that could satisfactorily do so while meeting the needs of our stakeholders, our team included stakeholders in our design processes, consulted experts (instead of making uninformed decisions) on topics outside of ours specialties, and considered the safety of the intended user, our team members, and any others that could potentially encounter our product. Our team also refrained from hiding any shortcomings of the project and fully embraced the nature of successive failure throughout the design process. Our team felt that our individual ethics met if not exceeded the ethics of the University of Michigan.

Recommendations

Wearable

The vest is a good start along with the straps that can fit a wide variety of people. The one concern may be comfort from the bottle caps on the users as it is pressing against their skin in different locations. A simple fix would be to 3D print more flush and rounded covers for the tactors. This can increase comfort and overall dimensions.

MATLAB

The script is a good foundation for what can be changed and tweaked regarding thresholds and storing of data coming from the Xsens dots. The one concern may be how the computer can process all 5 of the Xsens dots at once and be able to provide outputs appropriately based on a control schematic chosen by the researcher. There needs to be further investigation into the more specific latency of all 5 dots and sending outputs to the RPI.

Wiring

The wiring setup is at the point of supporting the capability to control the number of tactors desired of 17 but there needs to be further work in soldering more boards for the additional tactors. A proof of concept for 8 motors has been soldered and operates but for more tactors, it will require two additional arrays and more soldering. This leads to more hardware on how to store the boards with the RPI. It would be recommended to 3D print a simple box for storage of the boards to keep all electrical connections safe. The connectors for easy connections have been crimped and ready to plug but a better idea of wire management will need to be addressed in order to make the design work smoother.

Conclusions

Our task this semester was to create a wearable vibrotactile feedback device to be used by the Sienko Research Group to assist their research on individuals with gait disabilities and provide meaningful feedback to people who have these disabilities. Gait disabilities arise from a variety of health problems, from Parkinsons to vestibular problems, and have a negative effect on the quality of life of people with these disabilities. Gait disabilities make it more difficult to live an active lifestyle and be with friends and family. There is a need to help people who have these disabilities. The method that was chosen to assist these individuals was the development of a feedback device that can help people with these disabilities learn to walk with better form and learn to walk comfortably so they can have a fulfilling lifestyle.

Previous attempts to create a device that assists with balance exist. The Sienko Research group has previously created a device that helps with the standing balance of individuals with these same gait/balance disorders. Other benchmarking showed that many devices had been made to help with balance, using a variety of forms of feedback from vibrotactile to audio, but very few devices were designed to aid individuals with their walking, or gait. Also, no devices were created to give feedback to the entire body, something that is unique to our design. And finally, no other devices embrace the new idea of giving implicit feedback to participants. Our feedback is unique in that it can work both explicitly and implicitly. Explicit feedback means giving a vibration or some other form of feedback directly to the part of the body that is doing something wrong. For example if someone was leaning too far forward, a buzz on their forehead might indicate that they should lean further back. Implicit feedback is different in that it allows participants to make their own conclusions about what feedback they are receiving, something that could be beneficial to long term improvement of gait. In the case of our design our sponsors recommended creating an implicit array of motors. The idea behind an array is that a pattern of vibrations across a patient's torso could be shown to the patient, and the goal of the patient would be to walk in a manner that causes that pattern to reappear. The idea is that this allows the patient to iterate upon their gait by themselves instead of growing dependent on a device to balance for them.

Based on the description of our problem, and the initial recommendations put forward by our stakeholders, we began to develop concepts for our design. While some parts of our design were already set, like our device being wearable and vibrotactile, other parts could be decided by our group. After iterating several times, our final design was chosen to use Xsens Dot sensors to collect the gait data from the wearer, coin motors to provide the feedback at several locations of the body, a 3x3 implicit feedback array on the back of the wearer's torso, and a vest and straps to connect the coin motors, battery, Raspberry Pi, and sensors to the body. A collection of these components is shown below.

Figure 38: This figure shows most of the components that were used in our final design. We used an adjustable vest, straps and headband, as well as Xsens Dots, a Raspberry Pi, and coin motors to make our device.

These components were all used together to create our final prototype. A large part of our engineering analysis was done in the selection of these components. Because several of our requirements and specifications had to do with wearability, feedback, and latency of the device, we made sure to analyze several options for each component and we chose components that met our specifications.

The way our solution works is by having Xsens Dot sensors communicate wirelessly through MATLAB, where MATLAB extracts the important data from these sensors and outputs signals to a Raspberry Pi based on logic in the MATLAB script. The Raspberry Pi is located on the patient's body and is wired to coin motors all over the participants body, some of which are on the head, arms, and legs to give explicit feedback, and some of which are on the patient's back where the implicit array is located. These coin motors are activated based on the signals from the Raspberry Pi which is also attached to batteries on the patient's torso. The result is a streamlined process that can work real time under most circumstances. Shown below is a schematic of the logic flow for our device.

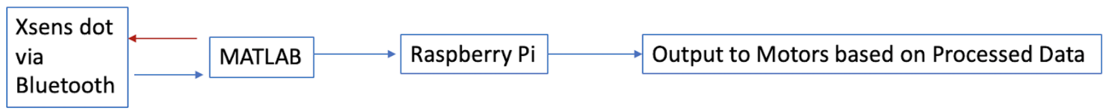


Figure 39: Flow chart showing how the Xsens Dot data makes it to our coin tactors.

We performed verification tests to ensure that our device met our stakeholder requirements and engineering specifications. We found that we met all of our most important requirements while missing out on a couple of the less critical ones. We found that our device was capable of gathering data on human gait, delivering that data to MATLAB, and outputting signals to our tactors all within a fraction of a second. This real time requirement was an important goal of our design which we were able to meet. Our device is adjustable for many body types, meeting another requirement of having a reconfigurable device that can work for the majority of people. And finally, our device was capable of delivering easy to feel feedback that was tested by members of our group. We were very satisfied with the performance of our design this semester.

The largest areas of improvement for our design lie in creating more firm connections in our wiring, and designing a user interface that is easy to use. Better wiring is already underway by using solder breadboards and crimped wire connections to make the device easily taken apart and put back together without worrying about the device breaking. A user interface is a future project that would be accomplished by designing an app that can be used to track patient trials and communicate with MATLAB and change the thresholds within MATLAB so different kinds of feedback can be given to the patient with minimal downtime between tests. Also in the future lies the validation of our design. This would be accomplished by speaking with medical professionals and physical therapists to see if our prototype is something they are interested in. Another validation test would be to actually use this device on people that have gait disabilities to see if the feedback we can give them is meaningful and useful.

Overall, we are excited about the work we completed this semester and optimistic about the future work with the device we have prototyped. While work still needs to be done before the device can be confidently used with people with real gait disorders, the proof of concept we have shown is promising and could have positive social and global impacts if the device was further improved and taken all of the way to market.

Acknowledgements

Our team would like to take this opportunity to acknowledge the help and contributions to this project from numerous people during our design process.

Safa Jabri, while being one of our sponsors, was also integral in helping us understand the shortcomings of previous groups, supplying us with prototyping tools to get a read on the project at an earlier point in time during the semester, as well as constantly being available for consultation. Safa was always giving great feedback not just from a stakeholder perspective, but also through a researcher perspective that became very valuable as our team moved into the final steps of our design process.

Dr. Kathleen Sienko was another primary stakeholder that our team worked with throughout the design process. Dr. Sienko gave the team invaluable information that helped with conducting research into gait problems as well as guidance to take a proper engineering design process to achieve a good final result.

Don Wirkner provided vital help and guidance to our team late in the design process to help with wiring schematics and supply a workplace and some materials to work on our wiring of the device.

Joanna Thielen helped our team early on with research into gait disorders and devices available on the market, providing us numerous resources and databases to look into. Her work as the library contact for our team was very helpful.

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Appendix A: Team Member Bios

Ravee Bakshi: Ravee Bakshi is a mechanical engineering student at the University of Michigan in the last semester of his undergraduate degree. Many of the interests include outdoor activities such as hiking and various sports.

The journey to becoming an engineer started in a STEM program in high school that exposed the many different sides of engineering. From there he began a mentorship program with Visteon working with instrument cluster validation in new vehicles. In the summer of 2019 up until currently had the opportunity to work with Professor Boehman as a Research Assistant working with various projects related to fuel and engine work. This led up to two different internships at Ford working with engine test methods and connected vehicle data to better improve test procedures.

Upon graduation, Ravee will be working at the Ford Motor Company in the electrified powertrain team helping scale Ford's efforts in electrifying their vehicle lineup.

Andre Senerpida: Andre Senerpida is an undergraduate mechanical engineering student at the University of Michigan. He plans to continue his education by pursuing a master's degree in automotive engineering during the fall of 2022. Andre has always had a passion for learning more about topics in STEM which has led him to participate in programs such as the Ford High School Science and Technology Program (HSSTP) and take on a minor in electrical engineering. His interests include running and mountain biking.

Andre started his college career at the University of Michigan-Dearborn during the fall of 2018 and later participated in his first internship with Ford analyzing fuel emissions and economy tests during the summer of 2020. He transferred to the University of Michigan during the Fall of 2020 and worked for Electric Last Mile Solutions (ELMS) as part of the occupant safety team and the reverse engineering team.

Andre is graduating with his bachelor's degree following the winter of 2022 and is planning to continue work with ELMS until the start of his first graduate semester during the fall of 2022.

Caleb Styles:
Caleb Styles is a mechanical engineering student at the University of Michigan. He will be pursuing his masters degree in mechanical engineering starting in the Fall of 2022 also at U of M. Caleb has spent almost all of his life in Canton MI and grew up around automotive engineering. He became interested in mechanical engineering himself through the STEM program at his high school, and his interest has continued to grow through his experience at university.

Caleb began his undergraduate education at the University of Michigan - Dearborn where he took his first internship in 2019 from Hanon Systems. There he worked with an electronics and fluid pressure team to validate new valves and pumps used in a variety of vehicle applications. After this internship he transferred to U of M Ann Arbor where he worked with professor Andre Boehman on studying the practicality of renewable diesel fuels and working with the Ford 6.7L powerstroke engine. He also interned with Garrett Motion where he studied the migration of the balance of turbochargers after being used in a vehicle for its first time.

Currently Caleb is set to intern with Ford in the summer of 2022 and plans to either pursue a PhD in mechanical engineering or take an engineering position after he finishes his masters degree in the Spring of 2023.

Joseph Towianski
Joseph Towianski is a mechanical engineering student pursuing a bachelor's degree in mechanical engineering from the University of Michigan. Joe grew up in Milford MI right in the backyard of the General Motors proving grounds so the automotive industry is in his blood. He became interested in the automotive industry through a love of auto racing like NASCAR and INDYCAR.

Joe began university in Dearborn at the University of Michigan-Dearborn before transferring to the Ann Arbor campus in fall of 2020. During the summer of 2020, he founded his own internet broadcasting brand, JTN, where live online sim-racing is broadcasted weekly.

Currently Joe is on track to receive his bachelor's degree in the spring of 2023.

Appendix B: Benchmarking Device Photographs

This appendix contains photographs and descriptions of the devices mentioned in the benchmarking portion of this report. Each device is shown first, then described after the photo introduction.

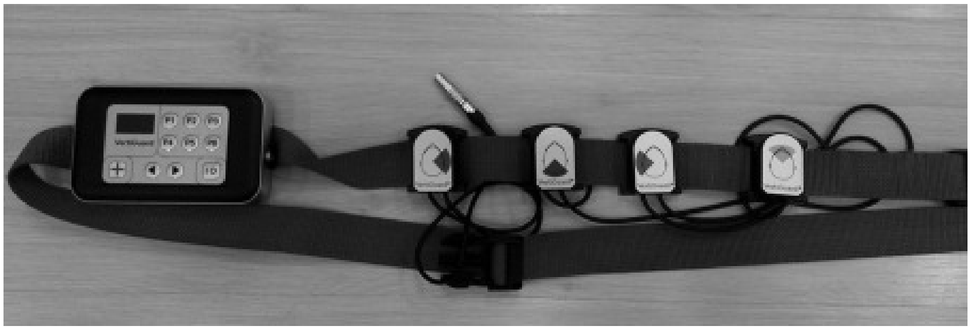

Figure B.1. The Vertigaurd [8] vibrotactile feedback belt. This device contains both the IMUs to track movement and motors that provide the vibrotactile feedback around the torso. The belt contains two gyroscopes and is used as a trainer to help improve an individual's balance. The four vibrating motors are placed 90 degrees from each other, and signal the direction of body displacement.

Figure B.2. Sway Star/Balance Freedom [9] is a combination of a tool to measure a patient's balance and gait, sway star, along with a vibrotactile and audio feedback device, balance freedom. Seen on the right is the Sway Star device that is used to examine the gait patterns and detect irregularities. This system is then hooked to the Balance Freedom system, seen on the right, which can provide both audio and vibrotactile feedback.

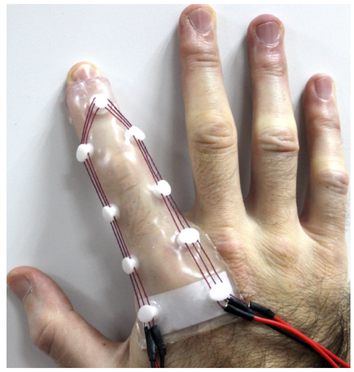

Figure B.3. The STJU research device constructed to provide feedback to a participant. The devices created in this study are experimental in nature as a way to both analyze and provide training for body movement. [10]

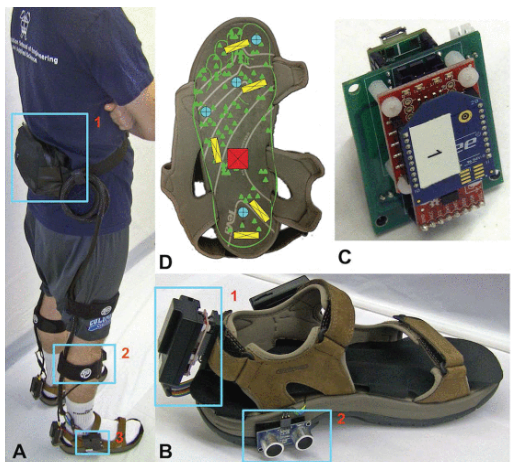

Figure B.4. Sole Sound is a vibrotactile device that consists of vibrating motors that are placed on the shoes to provide vibrotactile feedback, along with IMUs that track the foot angle [11]. This device can be attached to a variety of shoe sizes.

Figure B.5. An empathy based haptic feedback device created to provide not only vibrotactile feedback to a patient but also to their clinician. IMU data is tracked on the patient and the vests are paired to provide both individuals with the same feedback, so the clinician can gain a better understanding of the feedback that they patient is getting. [12]

Figure B.6. The vibrotactile feedback device used by the Sienko Research Group in a 2013 report on the effect of vibrotactile feedback on postural sway [1]. This device has tactors and sensors located on the waist and was used as a proof of concept for explicit vibrotactile feedback.

Figure B.7. This device contains foot sensors to monitor gait and is combined with a belt that provides explicit feedback at the participants waist [13]. It is also empathy based, as the researcher receives the same waist feedback while also receiving foot feedback corresponding to the participants gait.

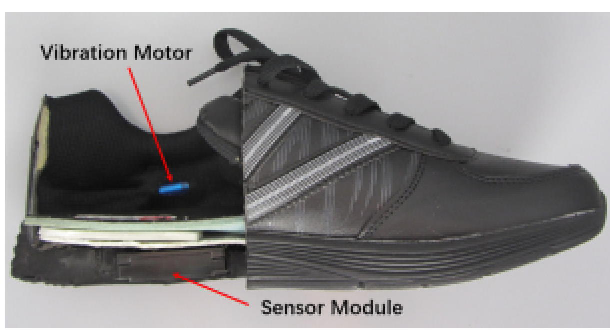

Figure B.8. [14] This device consists of two vibration motors on the medial and lateral inner surface of a shoe and a sensor module embedded within the shoe that includes a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. If a preset foot progression angle threshold is exceeded, the motors will give feedback to the user in real-time.

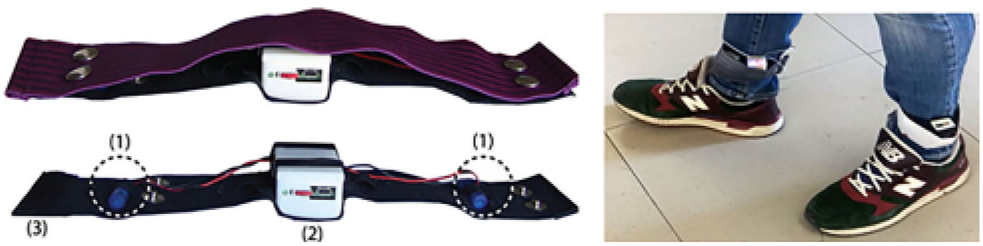

Figure B.9. The WEARHAP-PD device has two vibrating motors attached to an elastic band that is attached to the ankle. Total body motion was tracked using Vicon motion capture equipment which collected data on participant gaits. [15]

Appendix C: Bill of Materials

Part no.	Part Name	Links	Quantity	Cost/unit	Cost	Notes
1	XSens Dot Motion Sensors (IMUs)	Link	1	$620.00	$620.00	Each set has 5 sensors; provided by Sienko Research Group
2	INEED Coin Motor (C0820BE03L27)	Link	20	$2.40	$48.00	Pricing is by tray size and the closest to 16 is two trays of 20
3	20 Gauge wire	Link	1	$14.95	$14.95	6 spools are included in this kit
4	Raspberry Pi 4 (Extreme Kit)	Link	1	$169.95	$169.95	
5	Wiring Connector	Link	2	$12.00	$24.00	12 pcs per set
6	Solder Seal Wire Connectors	Link	1	$18.95	$18.95	250 pcs per set
7	GPIO PIn Extender	Link	1	$9.99	$9.99	
8	VELCRO Brand Straps	Link	1	$19.56	$19.56	25 per set
9	Himal Sports Vest	Link	1	$29.99	$29.99	It's on sale for right now but it may revert back to $59.99
10	LUCKYGO Head band	Link	1	$8.98	$8.98	2-pack of headbands
11	TP-Link Bluetooth Adapter	Link	2	$14.99	$29.98	
12	Nilight Wiring Connectors	Link	1	$18.78	$18.78	
13	SD Card	Link	1	$8.25	$8.25	
14	10,000 mAh Battery Pack	Link	1	$39.95	$39.95	Provided by Sienko Research Group
15	BJT Array 8 NPN Darlington ULN2803A	Link	4	$12.63	$12.63	Provided by Sienko Research Group
16	Tenergy 2 Pack 2000 mAh Rechargeable Battery Pack	Link	1	$16.99	$16.99	Provided by Sienko Research Group
17	Solder Boards	–	6	–	–	From Mechatronics Lab
				Total	$1090.95	

Appendix D: Project Plan

Our team's project plan through the end of the semester is listed below.

(02/12/22) - Concept Generation Strategy

Ravee- Brainstorm efficient concept generation strategy to keep potential designs organized.
Joe- Brainstorm efficient concept generation strategy to keep potential designs organized.
Andre- Brainstorm efficient concept generation strategy to keep potential designs organized.
Caleb- Brainstorm efficient concept generation strategy to keep potential designs organized.

(02/19/22) - Beginning of Design Concept Generation

Ravee- Develop one design solution that meets the design requirements including a design sketch with labels and detailed plan for parts and sensors to source.
Joe- Develop one design solution that meets the design requirements including a design sketch with labels
Andre-Develop one design solution that meets the design requirements including a design sketch with labels
Caleb- Develop one design solution that meets the design requirements including a design sketch with labels
Group- By the end of the week share with the group the rough designs to get an idea of where we are at

(02/26/22) - Evaluating Design Concepts

Ravee- Start building the design selection matrix for choosing the best design
Joe- Create a presentation format to clearly show all four designs to help compare and contrast
Andre- Begin developing a more in depth analysis plan for the designs
Caleb- Begin making a document for taking detailed notes on the selection process as a group
Group- Come to a conclusion for which design meets the requirements and specifications the best or combine different aspects of each design into one cohesive design. Speak with stakeholders on the potential designs and final to get input on feasibility.

(03/05/22) - Final Design Plan

Ravee- Generate potential CAD pieces and sketches for the chosen final design
Joe- Put together a final list of all the components and parts needed for the design with potential roadblocks for accessibility
Andre-Help generating CAD and sketches
Caleb- Develop a list of potential sensors, motors, fasteners that could work for the final design along with matrix to choose which components will be chosen
Group- Finalize presentation as a whole to make sure flows properly

(03/10/22) - DR 2 Presentation

Ravee-Develop a plan to handle any potential shortcomings for the final design along with slides covering consent generation strategy and design that was come up with
Joe- Build slides regarding own design and aspects of it along with final design summary
Andre- Build slides regarding own design and design matrix for choosing design and combining into one final design. Also, building project schedule for up to DR3
Caleb- Build slides regarding own design and talk specifics of final design including the parts and justification for why parts were chosen.

(03/14/22) - Initial Final Solution/Beginning Engineering Analysis

Ravee- Finalize battery analysis for the Raspberry Pi and tactors
Joe- Creating Final sketches that go along with the initial final solution
Andre- Begin getting the Raspberry Pi ready for Mwireless compatibility
Caleb- Creating final sketches and confirming the final solution
Group- Confirm the final solution to ensure it meets all expectations from stakeholders along with requirements, Finish up DR2 report

(03/19/22) - Engineering Analysis

Ravee- Help with getting Raspberry Pi to interface with Imu and the tactors individually
Joe- Finding theoretical values for the number of force wires that can withstand
Andre- Help with finalizing battery capacity along with proper documentation
Caleb- Begin getting IMU and Raspberry Pi to interface with each other to collect data
Group- Finalize Engineering analysis needing to be done for DR3 along with getting Raspberry Pi and motors interfacing with each other

(03/28/22) - Validation and Risk Plan

Ravee- Continue working on Raspberry Pi compatibility with IMUs and create a list of risks and plans to overcome those risks
Joe- Develop a more detailed plan for making sure design can be validated
Andre- Continue working on Raspberry Pi compatibility with IMUs
Caleb- Continue working on Raspberry Pi compatibility with IMUs
Group- Develop a validation plan and risk plan

(04/04/22) - Design Construction and Testing

Ravee- Find ways to output data to RPi from MATLAB, test wiring connections
Joe- Assemble components of each subsystem
Andre- Find ways to output data to RPi from MATLAB, analyze complete electrical circuit
Caleb- Develop MATLAB logic to output signals to RPi
Group- Continue testing to eliminate any design uncertainties

(04/11/22) - Design Validation and Verification

Ravee- Finalize testing wiring connections
Joe- Test size and adjustability specifications
Andre- Test Safety specifications
Caleb- Validate (with stakeholders) and test MATLAB logic to output signals
Group- Finalize validation for design expo (including performance specs) and verify work with stakeholders, finalize verification of requirements and specifications

(04/18/22) - Final Verification and Documentation

Ravee- Create signal flow diagram
Joe- Create physical subsystems map
Andre- create wiring diagram
Caleb- finalize researcher interface
Group- Make any necessary modifications for final delivery to stakeholders (including safety and instructional documentation), finalize stakeholder validation

Appendix E: Manufacturing Plan

To assemble the device that has been created for the Sienko Research group, start by gathering all of the materials listed in the bill of materials.

Vest Construction

To create the vest that acts as the focal point of the device, start by gathering the Himal Sports Vest, adhesive velcro dots, and a sewing needle and thread. Place the velcro dots on the back face of the vest, first with the adhesive that is already on the backside of the velcro. After the velcro dots are attached with the adhesive to the back of the vest in the 3x3 pattern shown in Figure E1, start to sew the dots down to the back of the vest. By sewing the dots in, we are able to improve the attachment and keep the vest itself machine wash safe. Since this vest is launderable, it will make cleaning it between trials much easier for the researcher. Figure E2 contains a picture of the vest with the dots sewn into the back of the vest.

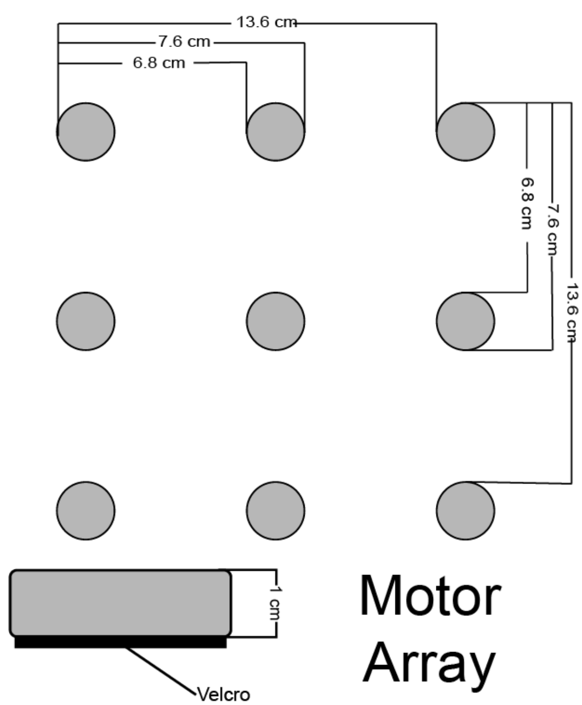

Figure E1. 3x3 Vibrotactile Array measurements

Figure E2. Vest with Array Velcro attached

Tactor Covers

The covers designed for the purpose of our design project are made of plastic water bottle caps, cardboard, and the velcro dots. To start, cut a hole in the side of the bottle cap. This hole needs to be large enough to allow for the tactor wires to come out freely. Next, take a coin motor and peel off the adhesive, placing the motor in the center of the inside of the cap. After the motor has been attached, take the cap and trace it on some cardboard, then cut out the cardboard circle to make the bottom of the tactor cover. The cardboard side will then have the velcro dot, the hard plastic side, attached with the adhesive that resides on the velcro's back. This will allow for attachment to any of the armbands or locations sewn on the back of the vest. Figure E3 shows a complete tactor cover, with the heat shrink solder connectors on the ends of the wire, as well as the CAD from solidworks showing what this looks like from the top.

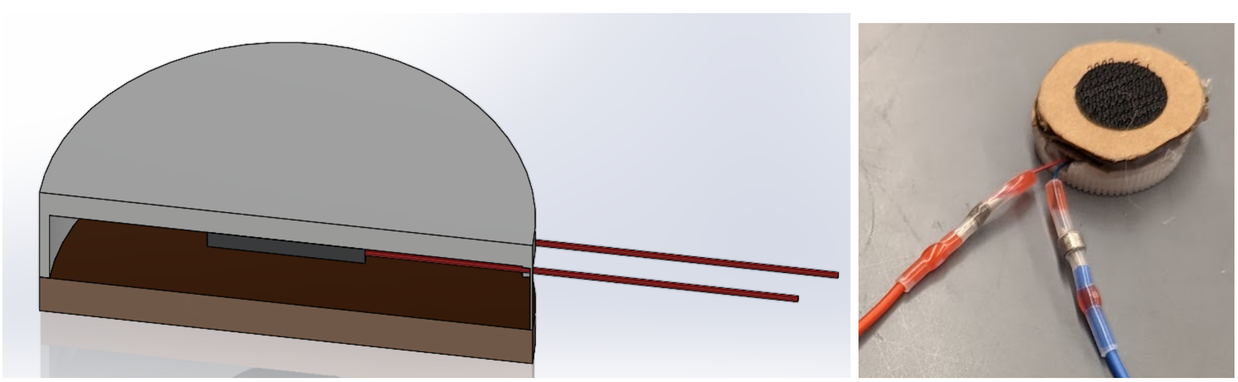

Figure E3. Completed bottle cap tactor cover.

Wiring
The device that has been produced utilized heat shrinking solder connections as well as a soldered breadboard to make connections. A wiring diagram can be found in Figure E4. The GPIO pins used on the Raspberry Pi are labeled in the MATLAB Code, and correspond to sending a power input to one motor each.

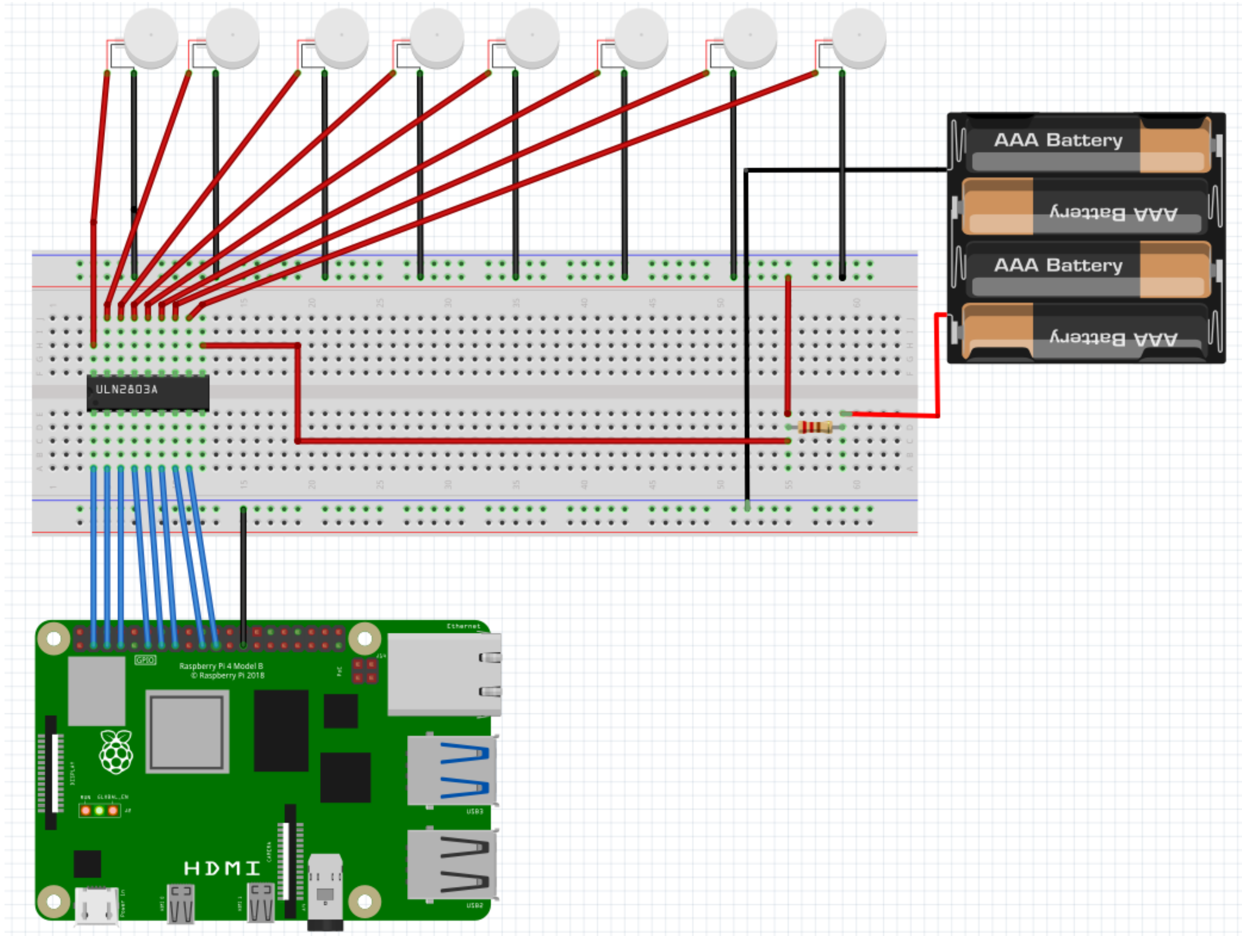

Figure E4. Wiring diagram of device

Connections to the breadboard are made through traditional soldering techniques, with the layout shown in the previous figure. After these main connections are made with the wiring, the other end of the wire is stripped, and then the solder seal wire connector is used to join the wiring from the breadboard to the wiring end of the detachable connectors. This wiring is shown in figure E5. The wiring needs better cable management and would be a progression on this device given more time to work on it. Then in Figure E6, the same solder connectors are used to wire the other end of the detachable connectors and coin tactor motors.

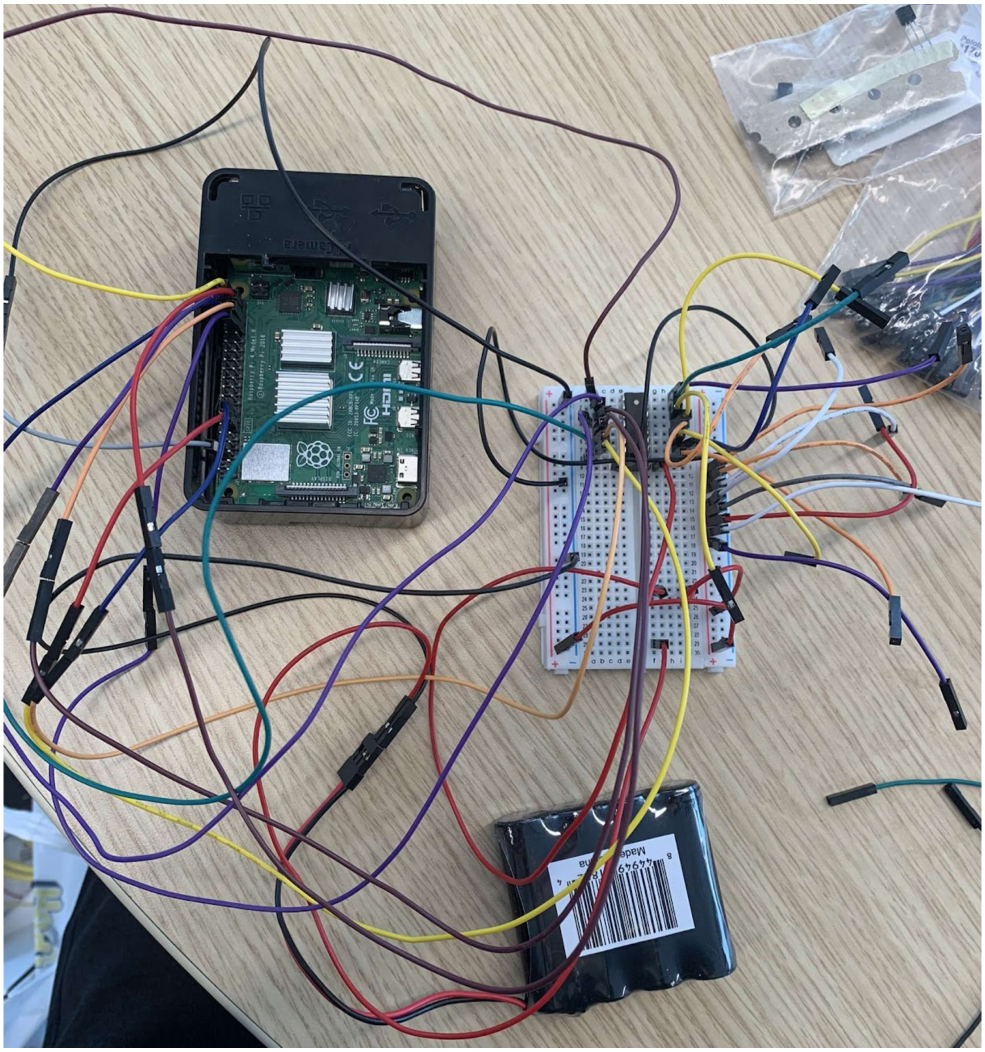

Figure E5. Wiring of the breadboard and raspberry pi.

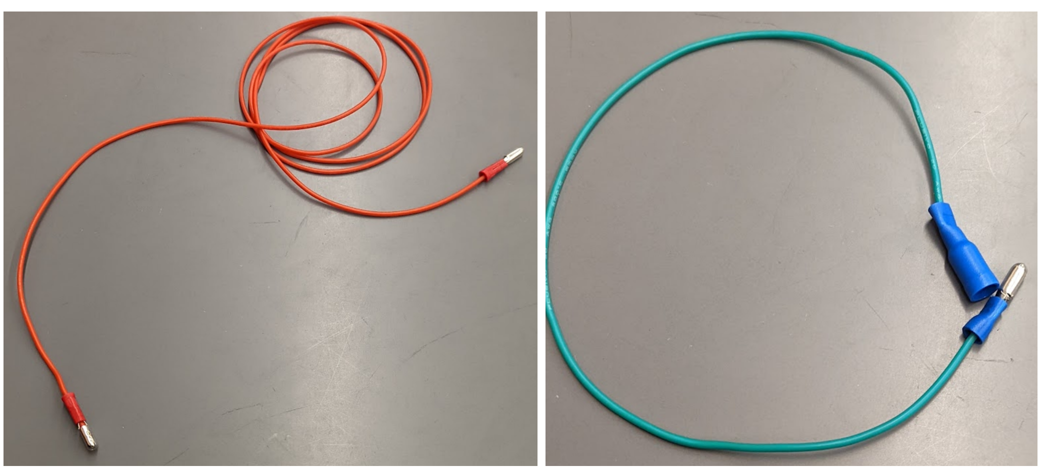

Figure E6. Detachable wiring connections

The wiring connections shown in Figure E6 allow for the detachment of tactors for when the device is not in use. The tactor end of the connections are shown in Figure E7. These connectors are created through the use of a crimping tool on the plastic pieces, with the stripped wire inserted into the connections. Wires that lead from the breadboard to the motors are male-male on each end, while the motors themselves have female ends on the wires.

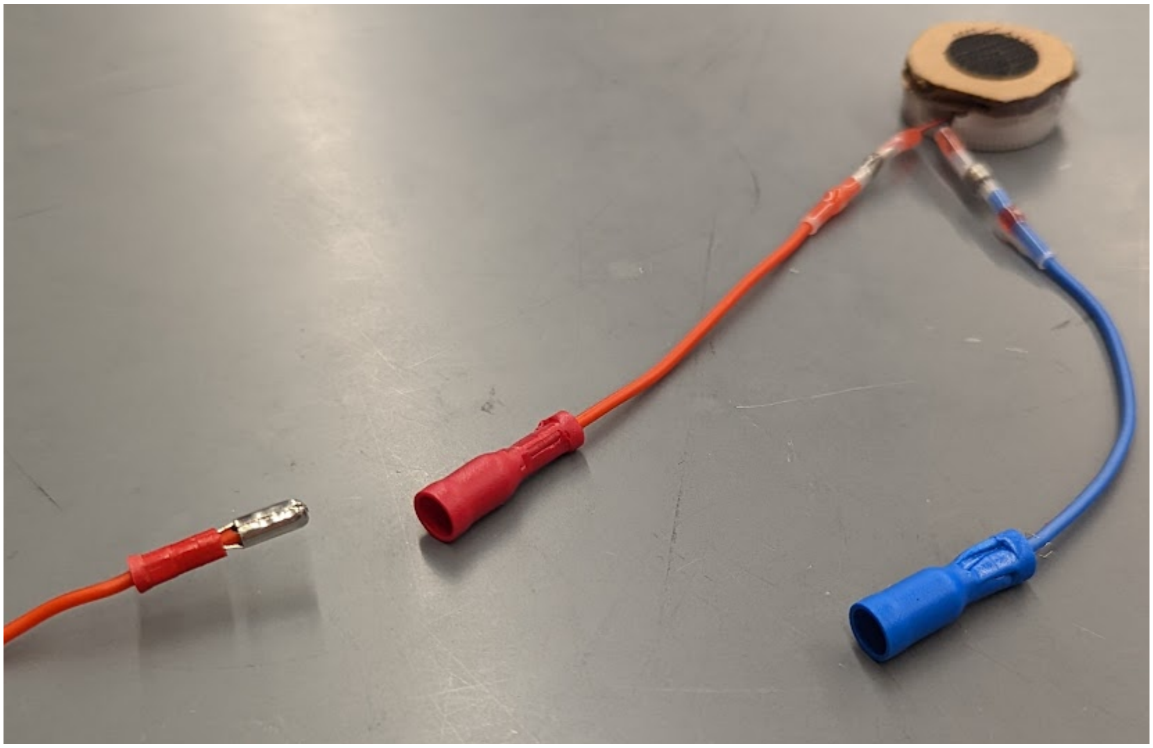

Figure E7. Crimped wire connections on end of coin motor leads.

Yellow wiring leads to legs.
Green wiring leads to arms.
Red corresponds to the head.
Blue connectors go to ground, red connectors go to the battery.

Appendix F: MATLAB Code Walkthrough and Process for Running

In this section, important commands, lines, and variables in the MATLAB code are provided, in addition to the comments left in the MATLAB files themselves. The single script will contain both initializing the Xsens dots to MATLAB and connecting the Raspberry PI.

The first step in running the whole system is following the RPI setup for MATLAB by going into the packages section and looking for the RPI hardware package. Once this begins installing it will walk through the setup. A computer must have the capability to insert a microSd card through adapters or directly through the computer. The install will flash a version of Raspbian OS with the correct network settings that must be entered. The suggested route is to setup wirelessly using enterprise setup with MWireless. From here you can enter the correct uniqname and password for the user. Once the setup is complete you will plug the microsd card back into the RPI and turn it on where you during the setup will test the connection. It is important to note the IP address, username, and password that will be displayed on the computer before setup is complete.

This first section of code is how MATLAB establishes a connection to the RPI and allows for a control over GPIO pins of interest.

```
%% PI TO MATLAB
crocpi = raspi('192.168.0.159','pi','raspberry')
```

FIGURE F1. RPI CONNECTION

The second stage in the code is how MATLAB searches for bluetooth devices using a scan tool to search what bluetooth devices are around the area. The next step is assign all the dots to a variable in matlab using the BLE command along with the MAC address for each of the dots.

```
clear
scan = blelist("Timeout", 10) %scan ble devices, set the timeout 10secs.
DOT_Measure_ServiceUUID = "15172000-4947-11E9-8646-D663BD873D93";
DOT_Control_CharacteristicUUID = "15172001-4947-11E9-8646-D663BD873D93";
DOT_ShortPayload_CharacteristicUUID = "15172004-4947-11E9-8646-D663BD873D93";
Heading_Reset_Control_CharacteristicUUID = "15172006-4947-11E9-8646-D663BD873D93";
Select_Orientation_Euler = [01, 01, 04 ]; %Select the data output type, 04 means Euler Angles(Roll, Pitch, Yaw).
Select_Orientation_Quaternion = [01, 01, 05 ]; %Select the data output type, 05 means Quaternions(w, x, y, z).
Heading_Reset_Buffer = [01,00];

P01 = ble("D422CD000AFD"); %Change P01 to your own DOT's tag name, Change the MAC Address to your own senso
%%
EnableP01 = characteristic(P01, DOT_Measure_ServiceUUID, DOT_Control_CharacteristicUUID);
write( EnableP01, Select_Orientation_Euler); % You can change to your desired payload mode.
P01Dataoutput = characteristic(P01, DOT_Measure_ServiceUUID, DOT_ShortPayload_CharacteristicUUID); % You ca
subscribe(P01Dataoutput);
Heading_Reset_P01 = characteristic(P01, DOT_Measure_ServiceUUID, Heading_Reset_Control_CharacteristicUUID);
write( Heading_Reset_P01, Heading_Reset_Buffer);
```

FIGURE F2. Xsens Dots Initialization

The next section deals with the way the for loop works for collecting the data. The first p[arameter that should be changed based on the duration of time is the count number. This is relatively how long it will run the script for and will determine the amount of data points collected and how the for loop processes the actual data. This then leads into sections of how data is stored within a matrix but also allows for customization of thresholds. It is important to write the feedback within the for loop so for every point of data that is streamed in. The code shown is a sample script for buzzing the motor based on roll angle of a user. The logic is to buzz the user if they are either falling forward or backwards too much.

```
% this is where we chance thresholds and rules ->
if ((P01Roll(i) > 80) && (P01Roll(i) < 100))

    writeDigitalPin(crocpi, 2, 0);
    writeDigitalPin(crocpi, 3, 0);
    writeDigitalPin(crocpi, 4, 0);
    writeDigitalPin(crocpi, 5, 0);
    writeDigitalPin(crocpi, 17, 0);
    writeDigitalPin(crocpi, 7, 0);
    writeDigitalPin(crocpi, 8, 0);
    writeDigitalPin(crocpi, 9, 0);
    writeDigitalPin(crocpi, 10, 0);

else if ((P01Roll(i) > 100) && (P01Roll(i) < 80))

    writeDigitalPin(crocpi, 2, 0);
    writeDigitalPin(crocpi, 3, 0);
    writeDigitalPin(crocpi, 4, 0);
    writeDigitalPin(crocpi, 5, 0);
    writeDigitalPin(crocpi, 17, 1);
    writeDigitalPin(crocpi, 7, 0);
    writeDigitalPin(crocpi, 8, 0);
    writeDigitalPin(crocpi, 9, 0);
    writeDigitalPin(crocpi, 10, 0);
    end
```

FIGURE F3. For Loop for Feedback and Collecting Data

The core of the script was found from github by user jiminghe with a mixture of changes and edits to RPI configuration and logic for motors to output. The link for the base code is included in the references under [33].