Customizable Wearable Vibrotactile Display for Gait Biofeedback Research

April 26th, 2021

ME 450 W21, Team 7
Do Hyun (Stu) Lee
Kai Myran
Kristina Nunez
Brady Oosse
David Wells

Instructor: Kathleen Sienko

Sponsors: Christopher DiCesare, Safa Jabri, Kathleen Sienko

Table of Contents

Table of Contents **2**

Executive Summary **4**

Problem Description and Background **6**

What are Vestibular Disorders? 6
Human Gait and Gait Cycle 6
Project Background 7
Project Goals 10
Biofeedback Modalities 11
Benchmarking 11

Stakeholder Engagement **16**

Requirements and Specifications **18**

Concept Generation **23**

Functional Decomposition 23
Brainstorming 24
Morphological Analysis 24

Concept Development **27**

Concept Evaluation/Selection **31**

Selected Concept **34**

Concept Evolution **39**

Design Drivers **41**

Design Driver #1 43
IMU Selection 43
Tactor Selection 46
Processor Selection 47
Design Driver #2 49
Design Driver #3 50
Design Driver #4 51
Design Driver #5 54
Design Drivers #6 & #7 56
Engineering Analysis Conclusion 57

Risk Analysis **58**

Risk to the Wearer 59
Risk of Device Malfunction 61

Detailed Design Solution **62**

Detailed Design Solution - Researcher Interface 62
Detailed Design Solution - Wearable 66

Verification **75**

Validation **83**

Discussion and Recommendations **84**

Conclusion **87**

Information Sources **89**

Authors **90**

Acknowledgements **91**

References **92**

Appendix A: Benchmarking of Designs and Subject Feedback **95**
A1. Commercially Available Wearable Biofeedback Devices for Static Balance and Gait Analysis 95
A2. Wearable Static Balance Devices Providing Vibrotactile Biofeedback used in Research 97
A3. Wearable Gait Analysis Devices Providing Vibrotactile Biofeedback used in Research 98
A4. Wearable Gait Biofeedback (Visual, Audio, Multimodal) Devices used in Research 101
A5. Various patents related to gait tracking and biofeedback research 103

Appendix B: Scripts using in Engineering Analysis **105**
B.1. Two tactor activation in Python 105
B.2. Two tactor activation with IMU data in Python 106
B.3. Two Tactor Activation in C++ 108

Appendix C: Researcher Interface Video Demo **109**

Appendix D: Researcher Interface README **110**

Appendix E: Bill of Materials **111**

Appendix F: Supplemental Information **112**
F.1. Engineering Standards 112
F.2. Engineering Inclusivity 112
F.3. Environmental Context 113
F.4. Social Context 113
F.5. Ethical Decision Making 114

Executive Summary

Approximately "35% of U.S. adults age 40 years and older had evidence of balance dysfunction" [1] which can lead to a fear of falling, activity avoidance, and an increasingly sedentary lifestyle. With such a large statistic, a solution is necessary to reduce this percentage and ensure a healthier U.S. population.

Some solutions already exist in the research and commercial space to analyze static balance and gait in people with vestibular disorders. In the commercial space, there exists products such as the SwayStar™ and the Balance Freedom™ which are some of many devices that utilize Inertial Measurement Units (IMUs), planar force sensors, motion tracking, and other sensing methods to characterize the gait of test subjects and provide feedback in the auditory, visual, and/or vibrotactile form to the test subject to correct their imbalances. Though these devices exist, they fall short in a number of key areas such as <u>full</u> gait characterization, biofeedback resolution, and testing scenarios. In detail, existing devices are limited to the number of gait characterizing sensors, limiting the parameters of the gait cycle that can accurately be characterized. Existing devices are also limited in biofeedback resolution due to a lack of available feedback modalities, quantity of feedback-delivering methods, and/or complexity of feedback methods. Finally, existing devices are limited in the scenarios that they test. Many of the wearable devices are used to provide feedback for static balance (as opposed to during gait), providing feedback when device wearers are swaying/the wearer is predicted to fall.

The goal of this project is to create a wearable device to be used in a research setting to explore the effects of implicit and explicit vibrotactile feedback on individuals with vestibular disorders (IWVD). This device must excel where current available devices do not. This means that it must effectively gather gait information and provide corresponding feedback that the device wearer can interpret to correct their balance irregularities within each testing trial. The wearable device must also simplify the task of altering testing scenarios and feedback settings for researchers conducting each testing trial.

Our team has utilized concept generation tools such as a morphological chart to formulate many combinations of concepts only to narrow the focus to one by utilizing design matrices and concept selection trees. As a result of these processes, and accompanying market research to understand the scope of each proposed concept combination, we propose a final concept for this project that we believe fits all the requirements and specifications outlined for the project. Utilizing straps to connect IMUs the the body, additional adhesives to attach tactors, and an elastic belt to house a tactoral array, processor, and battery, our design is centered around the idea that we have the option to provide implicit feedback or explicit feedback via the different locations of tactors and truly be a reconfigurable device wearable by anyone that is able to help with sensory-motor recovery by providing real-time cues to the test subject regarding their gait patterns.

This proposed final design concept requires a great focus on its subsystems and their functionality. To address this need, our team performed a number of engineering analyses. The analyses performed were market research analysis for commercially available IMUs, tactors, and processors, empirical testing, circuit simulation, physical circuit analysis and research regarding communication between design components. As a result of these analyses, we were able to understand restrictions in synergies between purchased IMUs, tactors, and processors, able to create a preliminary circuit for the full tactor

subassembly to be used in our wearable device prototype, purchase all of the required materials for our design, and create a full assembly able to record kinematic data as well as give vibrotactile output based on that data. For our verification testing, we ran multiple full simulations of the data collection and vibrotactile feedback process with a member of our team acting as a IWVD and the rest of the team as researchers to ensure that our design was fully functional and able to correctly sense motion and give feedback based on that motion without any risk to the wearer.

Although our proof of concept design is overall complete, there are multiple components that can be altered or replaced to reach a more complete, higher quality research tool to be used for multiple research trials. For example, the breadboard can be replaced (as the wires can be directly connected to the device), and some of the 3D printed parts can be removed in favor of stronger, more permanent solutions to ensure the longevity of the device.

For our next steps, we plan to hand our physical device over to our stakeholders on April 27th, 2021. To ensure that the transition will be smooth, we have prepared various instructional guides, step-by-step videos, and other supplementary materials to give to our stakeholders about how our device is run as well as various tips and tricks on its functionality.

Problem Description and Background

What are Vestibular Disorders?

Vestibular disorders, such as vestibular neuritis and vertigo, are medical issues that can affect the three semicircular canals and two otolith organs in your ears. These canals and organs detect rotary velocity and linear accelerations, and the information they gain is used by the Central Nervous System to help maintain our balance as well correct our posture. Vestibular disorders can be caused by various diseases, injuries, and medications that can cause damage to the vestibular system causing failure of the organs and canals themselves, of the cranial eighth nerve that transmits the information from the end organs to parts of the brain, and/or of the parts of the brain that process/integrate information from the vestibular system and other sensory systems [2]. Therefore, for people with vestibular disorders, it can be difficult to feel how exactly they're balanced/how their body is positioned in general. This can constantly be seen as an issue through walking or gait: a motion that is incredibly common but also requires a constant shifting in weight and balance throughout the entire body [3]. For people with vestibular disorders, there is a 12-fold increase in the chance of falling because of these impairments [4].

Human Gait and Gait Cycle

Gait is a person's pattern of walking, and it is a complex process involving coordination of muscles, bones, and nervous systems[5]. In a normal gait, a person swings the leg with the knee extended and the foot dorsiflexed. Then as the person moves forward, the heel touches the floor, also known as "heel strike". Plantar flexion follows this, occurring in the foot as it plants down on the floor, completing the "mid-stance". Following the "mid-stance", the "toe-off" occurs, and the foot pushes off the surface [6] . The full normal gait cycle is shown in Figure 1.

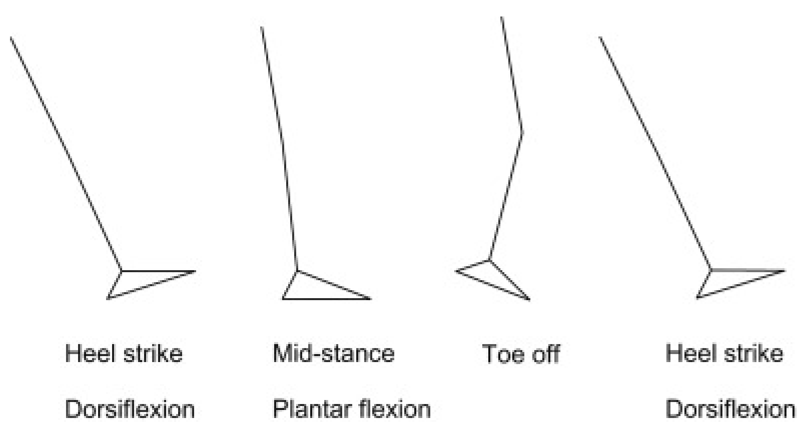


Figure 1 [6]: A normal gait cycle includes heel strike, midstance, and toe off.

A gait cycle represents the order of events that occur throughout a person's stride in order for them to move. As shown in Figure 2 below, the gait cycle is divided into two phases: the stance phase and the swing phase, each consisting of different gait movements. The stance phase is from "heel strike" to "toe off", where the foot touches the ground, and the swing phase occurs when the foot is off the ground, from "toe off" to "heel strike" [7]. The stance phase consists of four periods: loading response, mid-stance, terminal stance, and preswing. The swing phase encompasses three periods: initial swing, mid-swing, and terminal swing [7] . On average, stance phase and swing phase account for 60% and 40% of the gait cycle respectively [8,9]. Each leg is considered independently to define the gait cycle, as the legs will generally be in the opposite phase, except for a short period of overlap [8]. Across both phases, there are times when both feet are in contact with the floor, called double support. The first double support occurs at initial contact and lasts until the beginning of mid-stance, or about 10 - 12% of the gait cycle duration. The second occurs during terminal swing as the final "heel strike" of a cycle happens, also taking up about 10 - 12% of the gait cycle duration [7].

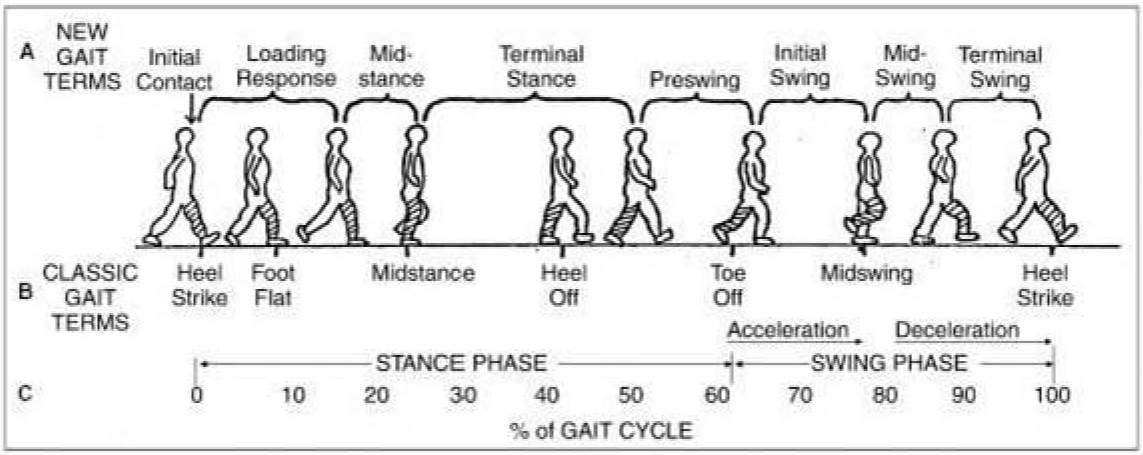


Figure 2 [7]: The gait cycle consists of two phases (stance phase and swing phase) with each phase consisting of varying gait movements.

A number of different parameters can be adjusted and observed during a gait cycle. The most prominent parameter that a person may change during gait is speed. Although to varying degrees, it has been observed that joint kinematics and movement patterns on the lower body, such as those of the hip, knees, and ankles, change as a function of gait speed [7].

For people with vestibular disorders, various aspects of their gait differ relative to the gait of healthy people due to decreased sensory information that helps stabilize the head and the gaze to maintain postural stability [10]. In comparison to healthy individuals, whose stride speed is 1.11 m/s, those with vestibular disorders, on average, have a significantly slower gait speed, being only about 0.84 m/s. The stride length also increased, meaning that the stride time and stride number to cover a similar distance as a healthy person was lower [11]. For the gait cycle itself, people with vestibular disorders spend a significantly longer time in the stance phase, where both feet are touching the ground, and a shorter average time in the swing phase [12]. This provides those with vestibular disorders more stability in their gait at the cost of speed. People with vestibular disorders also show increased step and stance width, particularly at faster gait speeds, in an effort to widen their base to improve balance [10].

Project Background

This project was proposed by the Sienko Research Group. This research group is well versed in the field of rehabilitation and aims to provide solutions that analyze static balance and gait in people with vestibular disorders. To achieve their goal, there is a need for the development of a customizable/reconfigurable wearable vibrotactile display to support the exploration of different biofeedback approaches for analyzing gait in a research setting. Specifically, a display is needed that is able to track and monitor the entire gait cycle repeatedly from start to finish. There is such a need for this exploration, given that individuals with balance dysfunction and patients who were clinically symptomatic "had a 12-fold increase in the odds of falling" [4].

Research tools used for balance currently exist, but most research and technology aimed at addressing the effects of balance in people with vestibular disorders are optimized for use with static balance control. The knowledge for static balance does not fully translate to gait analysis because it does not capture the full scope of a subject's activities (i.e. normal gait, climbing stairs, running, turning). Meanwhile, balance aids that do incorporate gait generally provide explicit vibrotactile feedback on one gait parameter, indicating exactly what movement to adjust and in what direction. In reality, there is an incredible complexity in providing feedback to a test subject, and many biofeedback approaches used in the balance aid research tools do not address this complexity and often only focus on providing the subject with explicit feedback as opposed to both implicit and explicit feedback. Providing explicit feedback can result in decreased gait velocity and abnormal gait when subjects try to implement that feedback in a testing environment because they focus on one gait parameter to alter and the rest of their body motion tends to be negatively affected. Meanwhile, implicit feedback can be more general and allows for the user to more seamlessly and naturally change their gait as opposed to cognitively pausing and thinking about exactly what to do [13]. However, this adjustment is not always perfect as the wearer is not told precise and direct instructions on the specific gait parameters feedback is being provided on. The wearer must determine what the implicit feedback is telling them overall.

This is backed by the studies conducted by researchers in the field of gait rehabilitation, and although our device will be focused on research as opposed to a purely rehabilitory mechanism, we deemed these findings informational and important to understand the entire scope of gait biofeedback in and of itself. Their works are cited below:

- "Polat et al. reported improved composite SOT scores for subjects undergoing a regimen combining static and dynamic training positions with electrotactile tongue feedback during ten 20-minute sessions over five days, compared to a control group which participated in an eight-week course of staged traditional vestibular rehabilitation and a loosely controlled home exercise program. However, the measured improvements were not retained for more than a few days." [4]
- "Two potentially negative side effects have emerged when subjects use sensory augmentation cues following limited training; subjects decrease their gait velocity and move in more of an "en bloc" manner." [4]
- "Only one published case study has examined usage over a large number of sessions; this study however, involved a single subject who performed 40 sessions with electrotactile tongue feedback and demonstrated balance improvements that persisted for eight weeks after the final session." [4]

To summarize these findings, research efforts to provide long-lasting, positive, retention to balance in test subjects have resulted in atrophying effects in the time after training, with the longest period without atrophy being eight weeks. Additionally, the current biofeedback methods utilized have altered the natural gait of subjects, resulting in abnormal movement patterns, body stiffening, and decreased gait velocities [4]. Gait analysis looks to determine if the use of biofeedback devices can result in retention (balance improvements for activities done in training do not decrease with time) and carry-over (balance improvements can translate to other activities that were not done in training) effects for daily activities after training with biofeedback devices [4].

Lasting positive carry-over effects of balance dysfunction rehabilitation are important because “a major barrier to performing long-term training studies is subjects’ unwillingness and/or inability to travel to a clinical or research setting for a large number of sessions.” [4]. Succinctly, there is a need for a biofeedback mechanism that can provide long-lasting positive effects on a subject’s balance and gait tendencies in real time while requiring that the subject does not invest ample time and resources in rehabilitation.

There has been extensive research done on developing a wearable biofeedback device to improve static balance, but there is an additional need for research on developing a wearable biofeedback device to improve gait. Static balance has the greatest instability in the sagittal plane, while walking balance has the greatest instability in the frontal plane [4] (Figure 3), so not all of the research for static balance can be applied to gait. Most research that has been done for gait analysis has focused on providing feedback on a single parameter of gait, but rehabilitation applications involve the interaction of many kinematic parameters [14]. There is a need for a rehabilitation platform that will enable multiple feedback approaches to be tested while looking at multiple gait parameters so that the research can, in the long-term, inform the development of a clinic-based and home-based biofeedback system.

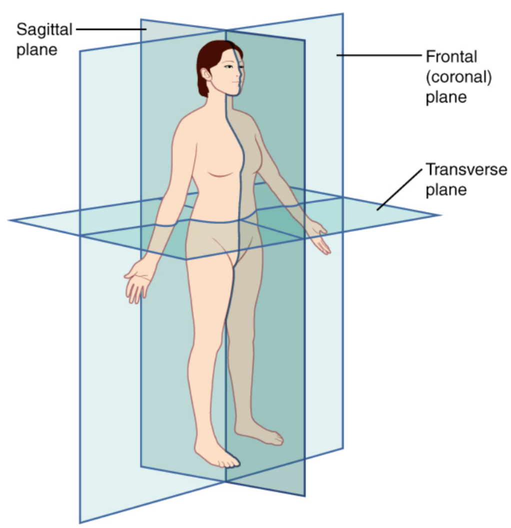


Figure 3 [15]**:** Anatomical planes.

Background research into the many research methods for effective gait rehabilitation has led our team to understand the potential benefits of varying biofeedback modalities. These modalities include, but are not limited to, auditory, visual, vibrotactile, and multimodal (a combination of at least two of the previously mentioned modalities). Out of the mentioned modalities, our team has chosen to move forward with the vibrotactile feedback modality, as some test subjects may have hearing or visual impairments.

Preliminary research has also been conducted to identify sensing sources. Out of the most promising sensing sources identified (planar force sensors, motion-tracking devices, and inertial measurement units). Inertial measurement units, or IMUs, were considered to be the most beneficial for the sensing needs of this project. This is due to the variability in placement on the human body for gait data collection that IMUs enable (infeasible by planar force sensors given they reside in the insoles of shoes) and that the sensors would move with the subject no matter how they move within a testing environment (infeasible by motion-tracking devices due to their stationary placement). The key demands from sensing sources are discussed in detail in the requirements and specifications section of this report.

Project Goals

The realization of the solution to this problem may fall outside of the scope of ME 450, but will come in the form of a new research platform that will be utilized by the Sienko Research Group to conduct gait analysis trials on their testing population. The solution will enable the investigation of multiple feedback approaches as well as multiple kinematic parameters related to gait. Ultimately, this research platform will inform the development of a clinic-based and home-based biofeedback system.

This research platform must embody the following core qualities:

- Features an effective biofeedback system for IWVD (individuals with vestibular disorders) that provides implicit and explicit feedback
- Features an effective researcher interface and processor capable of utilizing various different gait sensing/training algorithms
- Features potential for reconfiguration of sensors for measuring various gait parameters
- Features potential for reconfiguration of tactors for providing feedback to various locations
- Features a reconfigurable design to be able to fit and measure kinematic data for many different subjects

Regarding these features, explicit needs from a solution in this research space would be a device that is adjustable to fit a variety of body sizes and has variability in sensing sources (control over which section of the body to monitor) and tactor location, both of which can be parameterized over a researcher interface. This device would utilize tactile actuators (vibrotactors/tactors) with effective resolution for communication with subjects and would need to allow for multi-signal processing (i.e. signals from trunk movement and head movement, etc.).

If successful, this research platform will be an effective mechanism for providing researchers an effective way to analyze the effects of various gait parameters on balance and the effects of implicit and explicit feedback. Researchers will be able to reconfigure the device to allow changes to the locations of body motion being tracked and the locations where feedback is provided to understand the best possible ways to both track kinematic parameters as well as the best ways to provide biofeedback to the test subjects.

Biofeedback Modalities

Three common biofeedback modalities include auditory, visual, and vibrotactile. Auditory feedback can consist of voices or sounds. There is some evidence that suggests auditory feedback is effective at improving gait/dynamic balance [16]. Some challenges in successfully applying auditory feedback include subjects interpreting sounds as unpleasant and interfering with daily activities or overloading other senses [14,17]. Sensory overload is especially important because people with vestibular disorders rely heavily on alternate senses. Auditory feedback is also not effective for those with hearing loss [4].

Due to the research being done to make a wearable, in-home device static balance/gait biofeedback device, visual feedback is commonly displayed on a phone or tablet [18]. Similar to auditory feedback, there is heavily reliance on the sight sense [4], so visual feedback can sometimes interfere with interpreting natural stimuli [17]. When applying continuous visual feedback, the feedback cannot be seen for tasks with eyes closed or tasks involving head movements [4].

Vibrotactile feedback involves vibrations to the skin since the skin is a good information receptor [14]. Initial evidence suggests that placing vibrotactors on the head and trunk can help improve static balance [19]. Compared to auditory and visual feedback, vibrotactile feedback interferes less with other senses/natural stimuli [18]. Consequently though, vibrotactile feedback cannot portray as detailed information as other modalities, and reaction times are longer and depend on the body part stimulated [4].

Multimodal feedback consists of two or more feedback modalities. Multimodal feedback can supply more detailed feedback and be more versatile for all types of subjects. A challenge with applying multimodal feedback is that the feedback can occupy too many senses and become distracting or overstimulating while being incredibly costly to implement.

Feedback can also prompt either implicit or explicit learning. Explicit learning can be defined by direct and intentional instructions being given to a learner who must make a conscious and intentional effort to follow said instructions [20]. Implicit learning, on the other hand, involves giving more vague, disassociated instructions to a learner who must interpret and follow what they believe the instructions or signals to mean. The benefits of explicit learning are that there is zero question in the learner about what their expectations are, and they can focus and listen simply and intentionally. However, studies have shown that explicit feedback is less instinctual and can actually distract a learner from their natural actions as they focus on the direct instructions [13].Therefore, implicit learning has found to be just as, if not more, helpful as it fosters movement from the learner automatically as it requires less cognitive function.

Benchmarking

A number of commercially available and research based wearable biofeedback designs were researched. We were interested in the types of sensors used to track body motion, the location of sensors, the body motion parameters being tracked and provided feedback on, the type of biofeedback provided to the subject, and the method of body attachment. For vibrotactile feedback, we were interested in the number, configuration, and location of vibrotactors.

All of the devices fell into one of four groups:

1. Commercially available wearable devices for static and dynamic balance with biofeedback
2. Wearable static balance devices providing vibrotactile feedback used in research
3. Wearable gait analysis devices providing vibrotactile feedback used in research
4. Wearable gait analysis devices providing auditory, visual, or multimodal feedback used in research

Detailed information on each device is provided in Appendix A. We also look at various patents pertaining to wearable balance devices which are also provided in Appendix A. The devices available commercially are generally meant for real-time balance aids to be worn all the time. The devices used in research are mainly research tools to look at the effects of balance or gait and feedback. Providing feedback to the wearer is important because the feedback can be used to provide the wearer additional sensory information. This becomes especially important for people with vestibular disorders who generally need supplemental sensory information provided as they often unknowingly alter their gait due to balance dysfunction which increases their risk of falling.

Static balance devices generally track the body's center of pressure movement, ground force interactions, or trunk/head sway [18]. This is commonly done by placing IMUs on the back or the head, or by using plantar force sensors on the bottom of feet. The IMU signals are processed, and real-time feedback is provided to the wearer when the center of pressure (COP) is outside a predefined range or the trunk sway exceeds a predefined threshold. These devices utilize explicit feedback. Data about specific parameters (i.e. COP, trunk sway, etc.) are collected and feedback is provided on one parameter at a time with the wearer knowing what the feedback indicates. The wearer knows what parameter feedback is being given on and how to interpret the feedback (explicit feedback). There is evidence that research devices with IMUs and plantar force sensors can be used to improve static balance which will be further explained below.

Much of the progress that has been made on balance devices has involved static balance devices. While static balance is important for daily living, many daily activities involve dynamic activities, including walking, running, turning, and using stairs, which are not sufficiently addressed with static balance devices since dynamic movements involve much more complex kinematics than static balance movements. The progress made for static balance devices cannot be directly applied to dynamic balance devices due to limited knowledge of which body motion kinematics to measure, how to combine and process the resulting signals, and how to provide feedback to the subject [4,21]. Gait parameters commonly of interest in research include the start and duration of stance and leg swing, gait initiation, weight distribution, joint angles, stride lengths, step width, toe angles, continuity, toe clearance, trunk sway, and ability to turn [4,18].

In research done with dynamic balance devices, there is initial evidence suggesting that plantar force sensors can be used to improve dynamic balance [18]. Plantar force sensors are limited to being placed on the bottom of feet or on foot insoles. They collect data on ground-foot interaction forces, but they cannot track more complex motion of the head, joint angles, or limb coordination [18]. IMUs can collect data from a variety of body positions and allow a broader range of gait parameters to be investigated and a more complete set of kinematic body motion information. While there is a lack of promising research that has been done tracking dynamic balance using IMUs [18], the initial research has suggested that IMUs can be used to evaluate various gait parameters [9]. Research that has been done involving IMUs in dynamic balance devices generally place IMUs on the lower back to track trunk sway, the shank and thigh to track lower-limb join coordination, the head and trunk to track inclination angles [18], and/or the feet to track stride length, gait velocity, or foot angle [9,14]. The work does not address the knowledge gap on how to process and combine the IMU signals or how to provide the wearer feedback based on multiple signals.

For dynamic balance devices, feedback is commonly provided on only one gait parameter, usually trunk sway or pressure distribution on feet, but gait is complex, and one parameter does not address the entire gait aspect. Research done with feedback provided on only one gait parameter has also been shown to negatively affect overall limb coordination and body movement. Body stiffening [18], decreased gait velocity, and decreased secondary task performance [4] have been seen in research settings.

The dynamic balance devices available do not address these negative effects resulting from providing semi-real time feedback. They also do not have the capabilities to test a variety of feedback schemes or modalities. For devices using vibrotactile feedback, many provide vibrotactile feedback to single nodes throughout the body or to arrays in one body location. The arrays are limited in how they provide feedback as the activated column and row commonly indicate the direction and magnitude of trunk tilt. This way of providing feedback is an example of explicit feedback, where the wearer knows what gait parameter the feedback is being provided on and what the feedback indicates about that gait parameter.

None of the devices benchmarked have provided vibrotactile feedback schemes in different patterns that allow feedback on multiple gait parameters for a more complete kinematic picture of gait. This way of providing feedback would be an example of implicit feedback, where the wearer has not explicitly been told what the feedback indicates and they must figure out what the feedback indicates. Multiple gait parameters are combined into a feedback scheme provided to the wearer. The wearer must then determine what the feedback is telling them overall about their gait and their balance, as opposed to one parameter. The benchmarked devices also cannot easily transition between feedback modalities or different feedback configurations. Research cannot be done on multiple feedback approaches without the use of another device. A reconfigurable device would allow researchers to change locations of IMUs to collect data on different gait parameters and to change locations of tactors to provide feedback in different patterns or to different parts of the body.

The commercially available wearable devices are used for static and dynamic balance, but all of the sensors are located around the trunk, limiting the data that can be collected to analyze multiple gait parameters. The vibrotactile feedback is applied either to the head or the waist, but the devices do not have the capabilities to change sensor/tactor locations or test various feedback approaches.

Based on the benchmarked devices and our project goals, we further analyzed the wearable devices in all four groups based on two device aspects: the sensing capabilities (Table 1) and the feedback capabilities (Table 2) of the devices. A checkmark was given if the device was adequately successful in accomplishing the desired parameter while an X was given if the device did not have the capability to perform said action.

Table 1: Sensing capabilities of wearable devices used for static balance and gait analysis with biofeedback.

Devices	Can reconfigure sensing locations	Can track lower body movements (stride length, heel strike, etc.)	Can track mid-body movements (trunk sway, torso rotation, etc.)	Can track head movements	Can track wrist/hand movements	Has potential for additional IMUs for further movement exploration	Usable while freely walking (outside of a static lab setting)
Vertiguard [22]	X	X	✓	X	X	X	✓
SwayStar [23]	X	X	✓	X	X	X	✓
Balance Freedom [24]	X	X	✓	X	X	✓	✓
Janssen et al. [19]	✓	X	✓	✓	X	X	✓
Kingma et al. [17]	X	X	✓	X	X	X	✓
Xu et al. [14]	X	✓	✓	X	X	X	X
Ma, Zheng, Lee [25]	X	✓	X	X	X	X	✓
McKinney et al. [26]	X	✓	X	X	X	X	✓
Mazilu et al. [27]	X	✓	X	X	X	X	✓
Xu et al. [28]	X	✓	X	X	X	X	✓
Redd and Bamberg [29]	X	✓	X	X	X	X	✓
Biesmans and Markopoulos [16]	X	✓	X	X	X	X	✓

Table 2: Feedback capabilities of wearable devices used for static balance and gait analysis with biofeedback.

Devices	Able to provide vibrotactile feedback	Able to provide auditory feedback	Can provide semi-real time feedback	Provides explicit feedback	Provides implicit feedback	Ability to reconfigure feedback locations
Vertiguard [22]	✓	X	✓	✓	X	X
SwayStar [23]	X	X	X	X	X	X
Balance Freedom [24]	✓	✓	✓	✓	✓	X
Janssen et al. [19]	✓	X	✓	✓	X	✓
Kingma et al. [17]	✓	X	✓	✓	X	X
Xu et al. [14]	✓	X	✓	✓	X	X
Ma, Zheng, Lee [25]	✓	X	✓	✓	X	X
McKinney et al. [26]	✓	X	✓	✓	✓	X
Mazilu et al. [27]	X	✓	✓	✓	X	X
Xu et al. [28]	X	X	X	✓	✓	X
Redd and Bamberg [29]	✓	✓	✓	✓	✓	X
Biesmans and Markopoulos [16]	X	✓	X	✓	✓	X

As can be seen in Tables 1 and 2, there is no product on the market nor used in research that possesses all the capabilities that are required to achieve both the sensing standards and the feedback standards that we desire to achieve. Therefore, the need for a new product is evident, and there is an opportunity to develop a new, reconfigurable gait analysis/dynamic balance research tool. The device would collect data from multiple body locations using IMUs to monitor various gait parameters. The IMU signals would be processed to analyze more than just a single gait parameter (since gait involves many concurrent movements) to determine a vibrotactile feedback scheme to provide the wearer semi-real time feedback. Explicit feedback would be provided to individual body parts where tactors are also placed as the researchers would be able to notify the wearer that a certain vibration meant a certain action so that the wearer would know exactly what would be expected of them. Implicit feedback would be provided to an array of tactors on the trunk as when a certain pattern of vibrotactors on the trunk would be activated, it would be up to the wearer to interpret what that pattern meant and how to act. Implicit feedback could also be done via the individual tactors if no prior explanation of what the vibration meant was given to the wearer. The device would have the option of providing implicit and explicit feedback simultaneously, but currently we only plan on providing one or the other in a given trial. The device would allow different feedback approaches and different feedback schemes to be tested in a research setting. The device would also be reconfigurable. The IMUs would be placed at different body parts (or additional IMUs can be added) to enable researchers to track lower body movements, mid-body movements, head movements, and wrist/hand movements. The tactors would also be reconfigured to be placed at different body parts.

Stakeholder Engagement

As this project is based around creating a product not for commercialized use, but solely for a research environment, our stakeholders need to hold an incredibly prominent role throughout the entire design process. Our stakeholders include Safa Jabri, Chris DiCesare, and Prof. Kathleen Sienko. We were in communication with them weekly via email and met weekly over Zoom with our primary sponsors, Chris and Safa. We also meet once or twice a week with Professor Sienko. We feel as if this constant stream of communication is necessary to help create the best, most practical product by incorporating our stakeholders' feedback and input as much as possible. This process has proved incredibly beneficial as they have helped us with the ideation of many parts and pieces to our future design, including informing us how tactual actuators works (as well as how they want them to work for this product), what different sensors they had available and wanted us to use, and what positions of the body would be the good to consider attaching sensors to in order to gain the most amount of vital information about a person's gait. We used these answers to help guide our research, and, day-by-day, are gaining a greater understanding of the best way to implement their stated requirements and specifications as they have helped provide feedback as we iterate through many versions of specifications and requirements.

One potential benefit to interacting with our stakeholders throughout the design process is that, because the product is for them, they are able to guide and critique us as we conceptualize the product, letting us know exactly what they want, what they don't want, and any challenges they've seen throughout their research so far. In addition, because there are so few stakeholders that we have contact with, we won't constantly be torn between different stakeholders who have different views on where the product should go or what it should look like.

One potential challenge with interacting with our stakeholders throughout the design process is that, because they have had access to their lab and have physically done research trials on human gait already, their level of understanding, especially from a physical standpoint, is much higher than ours. Because of the COVID-19 pandemic and the health restrictions coming from it, we were not able to see the physical lab and the space where our product will be used or any research trials physically being run with their current set-up. Therefore, we found problems when trying to use concepts and ideation to fully understand a process and product that are physical, and our stakeholders, with so much more knowledge about the process than us, often have to explain even simple concepts in much more detail for us to understand them as we don't have this background knowledge of the physical trials and research itself.

As we developed concepts, we increased communication with our stakeholders, holding weekly meetings for them on Fridays where we discussed what changes and improvements we made on our concepts throughout each week. We specifically used them to further help mold our requirements and specifications as well as use their expertise as a guide for concept selection as they helped us towards making the most complete design that incorporates the best IMUs, tactors, and processors available within our monetary and conceptual limitations. We found this beneficial as Chris, Safa, and Prof. Sienko are all incredibly knowledgeable both about the research process in general but also in past failures and successes in the field of gait research. Therefore, they were wonderful mentors as they have been able to show us what papers to read, what key words and concepts to look into, and how to view this project not from the eyes of an inventor, but through the eyes of a researcher. Specifically, they pushed us to make flow charts for both the entire process itself (from a person moving all the way to the feedback being given based on their gait) as well as the information being processed which really helped us conceptualize and understand the entire process more. They also pushed us to look at everything analytically and with a final solution in mind so that we could focus on meeting goals and focus on achievement as opposed to simply providing a coming up with a vague concept. An example of this is when Safa suggested we look into IMU performance specifications such as Serial Baud rate and Magnetometer range and understand what they do so that we can apply them to our project as opposed to just keeping notes of them and comparing the values between IMUs without have a deeper understanding of why they we should be considering them.

We dealt with the challenges of virtual meetings by increasing our communication with our stakeholders so they can help describe and further flesh out the process for us. Additionally, we tried to use as many drawings and physical expressions of our design as we can so we can get as much of a physical sense of the process as possible without being able to actually do much in a physical, hands-on medium. We also saw that it was difficult to meet the differing desires of all of our stakeholders, despite having only three. There was some confusion on whether to have a smartphone or laptop researcher interface as well as if tactors needed to be located on individual limbs or purely in an array on the torso.

To address some of the challenges and confusion of only being able to meet virtually and not being able to show physical prototypes, we used a number of the last weekly meetings to present our progress on different subfunctions to get their feedback and show video demos. The subfunctions we showed included the user interface as well as the various straps of the physical component itself. For the user interface, we showed a number of iterations, each time implementing feedback on different features or usability aspects so the final design was best able to meet their needs. We also had video demos of the user interface to show exactly how the interface worked. For the physical components, we were able to show our stakeholders our design in its entirety via video call where they often gave feedback on where to put velcro connecting pieces, how exactly to stitch the elastic for maximum strength, where to use 3D printed parts vs. where not to use 3D printed parts, and much more. This feedback was incredibly vital to us as considering, as already mentioned, we were unable to run or even see any of their physical tests, so the expertise on the physical aspects and what they have noticed from their previous experience was incredibly vital.

Requirements and Specifications

The requirements and specifications for this project are listed below (Table 3). They are ranked in order of priority from highest to lowest. Note that certain specifications are written in blue text to indicate that they are subject to change based on further feedback from our stakeholders.

Table 3. Stakeholder requirements and specifications. Each requirement is ranked according to priority level, and includes a set of engineering specifications and their corresponding sources

Priority Level (High, Medium, Low)	Stakeholder Requirements	Engineering Specifications	Source
High	Wearable	1. Adults with no to severe vestibular conditions can walk with design ≥ 35m without interfering with arm or leg swing; design does not protrude from body ≥ 3.32cm 2. ≤ 2.5kg symmetrically distributed across the body 3. Tactors and IMUs do not fall off, slide ≥ 5.08 cm, or rotate ≥ 10 degrees in ≥ 2 hours	1. Interview #1; Interview #2; Sienko et. al, 2017 Cimolin et. al, 2012 Chen et. al, 2013 2. Abass et. al, 2017 3. Interview #2, #3, #4
High	Accommodates a variety of wearers	1. Fits heights from 149.8cm to 187.4cm 2. Fits head circumferences from 51.9cm to 60.0cm 3. Fits waist circumferences from 73.3cm to 132.6cm 4. Fits calf circumferences from 31.8cm to 47.1cm 5. Fits wrist circumferences from 13.8cm to 19.1cm	1. Moyer et. al, 2021 2. Young, 1993 3. Moyer et. al, 2021 4. McDowell et. al, 2008 5. Garrett, 1971
High	Semi-real time feedback	1. Vibration frequency can be provided to wearer (220 Hz -300 Hz) 2. Center-to-center tactor distance ≥ 20-30 mm 3. Able to process data and power equipment for ≥ 2 hours 4. Range of connection between processor and researcher interface display ≥ 5m	1. Interview #2; Kyung et. al, 2005; Bao, 2018 2. Van Erp 3. Interview #1 4. Interview #2, Interview #4
High	Kinematic Data Measurements	1. 5 IMUs placed on each leg, head, trunk and wrist 2. Able to process ≥ 5 signals 3. Receive and process data ≤ 2 seconds after kinematic motion is performed 4. IMU sampling frequency ≥ 100Hz 5. Range a. Accelerometer: ≥ ± 16g b. Gyroscope: ≥ ± 500 °/sec	1. Interview #1 2. Interview #2 3. Kathleen Sienko 2021, Interview # 4. Interview #4, Zhou, 2020 5. Mentiplay et. al, 2018; Agostini et. al, 2017

Priority Level (High, Medium, Low)	Stakeholder Requirements	Engineering Specifications	Source
High	Vibrotactile Feedback Display	1. Provide vibrotactile feedback to wearers in 5 separate locations (legs, head, torso, stomach, and potentially wrist) 2. Provide vibrotactile feedback in patterns in an array of 25 tactors on the torso	1. Interview #2 2. Interview #1
High	Interactive researcher user interface	1. Testing parameters (specific tactor activation, number of sensor signals collected) can be controlled via researcher interface every 30 seconds (between trials) 2. Trial settings, IMU data, and tactor on/off times can be saved to the researcher laptop once every two hours (at the end of each session)	1&2 Interview #2
Medium	Easy to set up	1. < 10 minutes to set up device on wearer 2. < 10 minutes to calibrate IMUs	1 & 2 Interview #2
Medium	Easy to clean	1. If fabric, can be cleaned by water/detergent in < 12 hours 2. If electronic, can be cleaned by sanitizing wipe in < 2 minutes	1&2 Interview #2
Low	Expandable to accommodate different modes of feedback	1. Able to accommodate auditory feedback (in addition to vibrotactile feedback) between 20 dB and 70 dB and between 3000 Hz and 4000 Hz	1. Interview #3, Pike 2017, Salvendy 2012
Low	Accommodate additional kinematic data sources	1. User interface can connect and process data from 2 additional IMUs	1. Interview #3

As defined by our stakeholders, the purpose of our project is to create a device that receives input from a human's movement to understand their gait tendencies and typical motion pattern. This function will be applied to research trials where the wearer will be tracked as they walk down a hallway, meaning that the final design must be able to follow the wearer's movements over a set distance. In order to accomplish this, our first stakeholder requirement was set to "Wearable". We quantified this requirement by specifying that the wearer, who may or may not have a vestibular disorder, is capable of walking a set distance with the device. The set distance (35 m) was decided after our stakeholders indicated that they wanted the wearer to be able to take 40 steps with the device. In order to find a distance that encompasses all possible wearers, we studied the typical step length of a "tall" man, or one in the 95th percentile in height, the demographic with the longest average step length. For ages 20 to 65, the typical step length of a "tall" man is 81.4 cm [31]. We then multiplied this step length by 40 steps, which resulted in a distance of 32.6 m. This was rounded up to 35 m to provide some room for error in case of a subject with an abnormally long gait. Additionally, as the device is meant to analyze and provide feedback on a wearer's gait, the final design cannot impede upon the wearer's range of motion or interfere with arm or leg swing, two features that encourage continuous gait [32]. This specification was quantified by the device protruding off the body less than 3.32 cm so that it would not be hit by the wearer's limbs during movement[33]. We also found that an additional weight of 2.5kg can begin to impact a person's natural gait [34], so our final design must weigh less than that. It must also be distributed across the body as symmetrically as possible, because any uneven weight addition can cause the wearer to have an unnatural lean in the direction of the weight [34]. Finally, we added a specification that the tactors and IMUs do not fall off, slide ≥ 5.08 cm, or rotate ≥ 10 degrees in ≥ 2 hours. This was set to ensure that the measurements from the IMUs and the vibrotactile feedback administered from the tactors occurred at the locations set by the stakeholders. Rotation can influence the data measurements from the IMU sensors, and also provide incorrect vibrotactile feedback. We obtained 10 degrees as our threshold based on a research study conducted to minimize sources of error in IMUs. Researchers were able to minimize sources of error by setting an initial reference posture to calculate the magnitude of displacement which reduced average residual error of the sensors to 10.7 degrees [35]. Error within this 10.7 degrees is unlikely to have a serious impact on IMU measurements, but extra rotation outside of this range could potentially influence data measurements to the point that incorrect vibrotactile feedback is administered. Assuming that our stakeholders implement a method of error reduction, we set our specification so that the IMUs will not rotate more than 10 degrees which is a more conservative estimate of the 10.7 degrees taken from this paper. We are less worried about IMUs sliding in-plane as long as they stay on the intended body part as the axes will stay aligned. However, if the IMUs slide a significant amount (> 5.08 cm), the IMU data might not be as expected because motion with a potential different radius of motion might be measured. This could cause a slight difference in data measurements and affect data processing.

In order to ensure that the device could be used by our stakeholders as well as any research participants they recruit, our next requirement is "Accommodates a variety of wearers." Upon discussion, our stakeholders informed us that their research participants can range from 18 to 85 years old. Given the possibility that our sensors and tactors may be mounted on the head, torso, legs, and wrist of the wearer, we researched height, head, waist, calf, and wrist measurements for the 5th to 95th percentile of adults in this age range. Based on this, we said that the device should fit heights from 149.8cm to 187.4cm [36], head circumferences from 51.89cm to 59.99cm [37], waist circumferences from 73.3cm to 132.6cm [36], calf circumferences from 31.8cm to 47.1cm [38], and wrist circumferences from 13.8cm to 19.1cm [39].

The third requirement is "semi-real time feedback." With this device, we want to be able to provide wearer feedback during the length of a trial. We expect trials to last approximately 30 seconds each, so it is not necessary to give feedback for the subsequent step. We expect cognitive and processing delays to be a non-issue because we are not providing feedback for the subsequent step, and the wearer will have the entire duration of the trial to interpret and implement feedback. Additionally, the researchers must be able to apply vibrotactile feedback with a frequency between 220 Hz and 300 Hz so that it is safe for the wearer and can still be easily sensed by the wearer. The distance between each tactor needs to be greater than the two point discrimination test for the body part selected as the location of the tactors. The two point discrimination test specifies the distance two distinct stimuli can be applied and humans can detect it as two distinct stimuli. For vibrotactile stimulation, we determined that the center-to-center distance of the tactors must be 20-30 mm to fulfill the two point discrimination test [40]. We also indicated that the device must be able to process data and power equipment for ≥ 2 hours, the maximum duration of a research session, in order to provide the wearer with semi-real time feedback without pausing the session [41]. Finally, our stakeholders indicated that they wanted the range of connection between the wearer and the user interface display to be ≥ 5. This was previously set to 35m so that the researcher could control the device settings while the wearer is walking down a hallway; however, after further discussion our stakeholders decided that they would only need to change these settings before and/or after each trial, and so a shorter range between the device and the user interface is appropriate.

Based on our stakeholders' feedback on our original set of requirements and specifications, we added the requirement "Kinematic Data Measurements" to ensure that the device could record kinematic features of the wearer's gait. To capture the full motion of a wearer's gait, our specification indicates that the design will have 5 IMUs placed on each leg, head, trunk and wrist to record the motion of these five critical components of gait [41]. Multiple IMUs allows us to look at each body part as the sum of the whole so we can have a more holistic view of how the entire body is behaving during gait. Given that there will be at least 5 IMUs, the design must also be able to process ≥ 5 signals so that the information from each IMU can be properly recorded and used to provide feedback to the wearer. The appropriate feedback to the wearer will require external post-processing algorithms of the IMU data in a compatible coding language. This post-processing must occur less than 2 seconds after the kinematic motion is performed in order to maintain semi-real time feedback. Additionally, the IMU sampling frequency must be ≥ 100Hz to ensure that the body kinematics are properly captured during use [42,43]. The final set of specifications involve key features of IMU performance, including accelerometer range, gyroscope range, and the accuracy of the accelerometer and gyroscope. The IMU accelerometer and gyroscope provide information on acceleration and angular velocity, and when these two data sets are combined, orientation and displacement data can be found. A study was conducted to determine what IMU features are important to consider for gait analysis research [43]. After testing several IMUs, the peak acceleration in the raw data was cut off for IMUs with accelerometer ranges less than ±16g. It was concluded that the loss of the peak acceleration data led to inaccurate movement trajectory estimation/shorter estimation of stride lengths. To ensure that our IMUs can collect all critical acceleration data, the accelerometer must have a range of at least ±16g. The IMU gyroscope must be able to capture the full angular velocity of the head, torso, legs, and wrist. Out of these body segments, the legs will have the largest peak angular velocity, which are no higher than 1000 deg/s [44]. Thus, our design will require IMUs with a gyroscope range of at least ±1000 deg/s.

Our next requirement is "Vibrotactile Feedback Display," which is the method by which the wearer will receive vibrations that indicate how they should correct their gait. Our specifications account for two different methods: the ability to provide feedback on 5 individual limbs ("provide vibrotactile feedback to wearers in 5 separate locations (legs, head, torso, stomach, and potentially wrist") and the ability to provide feedback via a set of learned vibration patterns ("provide vibrotactile feedback in patterns in an array of 25 tactors on the torso") [42,45]. These were the two methods that our stakeholders expressed interest in pursuing with the device, and so we set these specifications to ensure that this would be possible.

It is important to our stakeholders that they are able to control the device settings, and so we set a stakeholder requirement for an "Interactive researcher user interface". There are a few possible mediums through which this could be accomplished, such as a smartphone or laptop, but the main purpose of this interactive user interface is to allow researchers to edit testing parameters, specifically individual tactor activation, vibration frequency of the tactors, and number of sensor signals collected. Controlling specific tactor activation and vibration frequency is key to providing feedback to the wearer. This allows the researchers to explore different feedback patterns with each wearer and ultimately determine what serves as the most effective way of correcting a wearer's gait. The researchers also want to control the number of sensor signals so that they may add or remove sensors as they see fit. Ultimately, it is important for the researchers to have the flexibility to change these parameters at the start of each trial to accommodate future experimentation with the device. We estimated that each trial would take a minimum of about 30 seconds to complete based on the average walking speed (1.11 meter/second [2]) and the length of the hallway (35m). Thus, we indicated that the researchers should be able to set system parameter changes within 30 seconds of the last session to reflect the need to adjust the device at the start of each trial. Additionally, our stakeholders expressed that they did not want to spend time or effort into reconfiguring the device settings for every single trial, especially if similar settings can be applied to different trials throughout a session. This led to our specification "Trial settings, IMU data, and tactor on/off times can be saved to the researcher laptop once every two hours (at the end of each session)", so that our stakeholders can save time by saving preferences and reusing them in different trials.

Our next set of requirements are "Easy to set up" and "Easy to clean", both of which were explicitly requested from our stakeholders. "Easy to set up" was defined as the device taking less than 10 minutes to set up on the wearer.. This was set in the case that our stakeholders schedule research sessions back to back, in which case there is a short turn-around time for the device to be set for the next participant. For similar reasons, we also specified that it should take less than 10 minutes to calibrate IMUs. For the requirement "Easy to clean", specific cleaning methods were specified for possible device materials in order to ensure ease of sanitation. This includes electronic components, which must be able to be cleaned by a sanitation wipe within 2 minutes, and fabric, which must be washable using water and/or detergent in less than 12 hours.

Our final set of requirements, "Expandable to accommodate different modes of feedback" and "Accommodate additional kinematic data sources", were ranked as low priority. This is because these two requirements are meant for future variations of the device, and are not necessarily critical to our first design iteration.

The requirement "Expandable to accommodate different modes of feedback" was established to open the possibility of our stakeholders replacing vibrotactile feedback with an auditory mode. At this time, the best method of biofeedback for gait is not fully determined. Given this, although our stakeholders are currently focused on vibrotactile methods, they indicated that they may want to explore auditory methods of biofeedback while still using aspects of our design. Therefore, we created a specification for the device to be able accommodate auditory feedback (in addition to vibrotactile feedback) between 20 dB and 70 dB [46] and between 3000 Hz and 4000 Hz [30], as these are typical ranges for loudness and frequency of human speech.

The final requirement, "Accommodate additional kinematic data sources" is meant to allow the stakeholders to add more IMU sensors to our current design should they decide that they need to capture more kinematic data about the wearer's gait. We were told that they would use a maximum of 7 IMUs to track body motion, and so our specification indicates that the researcher user interface can connect and process data from 2 additional IMUs so that our stakeholders can make use of our design without making extreme changes to it in the future.

Concept Generation

As the first step in developing a design solution, our team explored methods to generate initial design concepts according to aforementioned solution requirements and specifications. Among numerous concept generation methods, our team selected functional decomposition, brainstorming, and morphological analysis as primary tools. First, by referring to our solution's requirements and specifications, we identified and compartmentalized the important sub-functions of our solution. Then, we brainstormed categories that were specification-driven that would be addressed by generated ideas. Finally, we generated a morphological chart based on the identified solution sub-functions and specifications. A main goal of our concept generation was to make sure that our design was inclusive for people of all sizes, ethnicities, sexes, races, backgrounds and ages within the 18-85 range and also that it did not pose any safety concerns with the electronic components or wires along the body.

Functional Decomposition

Functional decomposition is a series of steps to break down a large complex process or function into simpler, more comprehensible tasks. At the start of the concept exploration phase, we devised a functional decomposition diagram shown in Figure 4 below. The four categories that we determined sub-functions for were IMUs, tactors, processor, and researcher UI. For IMUs, we decided that body attachment method, data transmission methods, and power supply were important parameters for a functioning device. For tactors, the sub-functions that we determined were body attachment method, orientation, power supply, and communication method with the processor. For the processor, we selected body attachment method, body location, communication method with IMUs and tactors, and trial setting accessibility. Lastly, for the researcher UI, we identified platform, communication with the processor, and trial setting accessibility as important sub-functions.

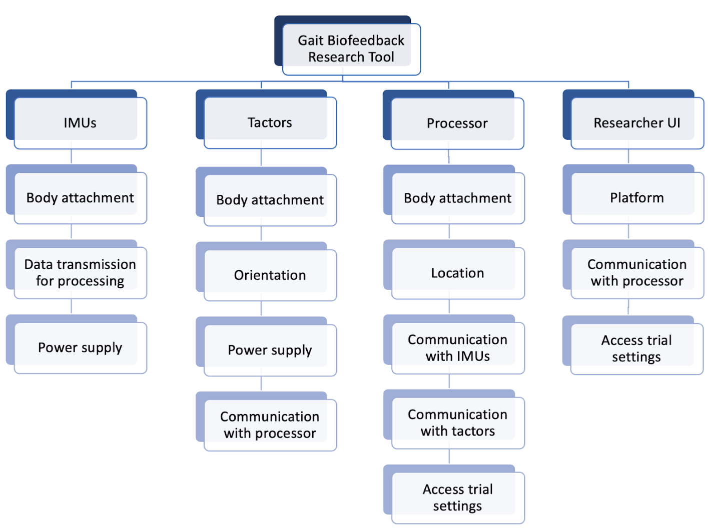


Figure 4: Functional decomposition diagram illustrating sub-functions and categories of our project based on specifications and requirements.

Utilizing functional decomposition allowed us to break down the overall function of the design solution to smaller, more manageable fragments of sub-functions so that we could determine what categories of specifications and parameters are needed for the design to function as intended. We worked with our stakeholders to develop a clear direction of the design and its sub-functions, so it made sense to us to use functional decomposition as the first step in the concept generation phase to ensure that we had accounted for the key sub-functions required for a functioning design. These sub-functions and categories were then considered for brainstorming.

Brainstorming

In the case of our project, we used brainstorming in the concept generation phase as a stepping stone to ultimately develop a morphological chart. After identifying the sub-functions through functional decomposition, we brainstormed ideas/concepts for each category. We also included sketches as this was a visual way for all team members to see a concept as well as to potentially spark a new idea. From our functional decomposition, the “body attachment” sub-function overlapped in multiple areas, so ideas were generated for a general sub-function of “body attachment” which was then further divided and specified into the body attachment methods for the tactors, IMU, and processor. Specifically, we first brainstormed ways to attach any of those to the body. After generating a number of general ideas, we then asked “Can this method of body attachment attach an IMU to the body?” to determine how well that concept would work for a more specific sub-function. We asked the same question for tactors and processors. At this stage of concept generation, we needed a large number of ideas—plausible or not—from each member of the team, and brainstorming was perfect for this purpose. We introduced numerous ideas for each category without fixating on the final solution, but not straying from the topic. As a result, we successfully generated a morphological chart that we will discuss in the next section.

Morphological Analysis

Morphological analysis is a method widely used to generate concepts systematically. It is used to analytically organize concepts for sub-functions identified through functional decomposition. Implementing this particular method, we generated a morphological chart, shown in Figure 5 below, to list and compare different concepts generated through brainstorming.

We agreed as a team that using morphological analysis would be advantageous in generating full design concept combinations as we could combine any combination of concepts from the sub-function in the morphological chart to create a full design concept. Since we worked with our stakeholders to define the direction of the design and its sub-functions, our task was to propose ideas for each sub-function, and combine them to generate full design concepts for evaluation. A morphological chart was perfect for this task since it clearly illustrated all the possible design combinations to assess.

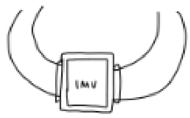
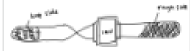
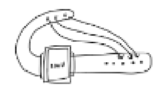
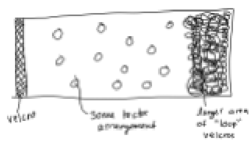
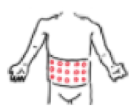
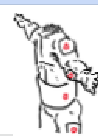
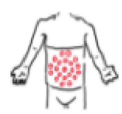
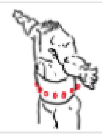
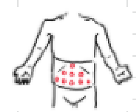
Function	Ideas/Concepts					
Attach IMU to body (method)	Straps	body suit	sticker	tape	clip (to pocket, to belt, ...)	elastic band
						
	clothes-pin (attach to shoe)	sweat band	resistant band material to tie around body	velcro	belt/watch clip	button band
						
Attach tactors to body (method)	Straps	body suit	tape	sweat band		
						
	velcro	button band	elastic band	resistant band material to tie around body		
Tactor Orientation	nxn grid	Individual Points	Circle	Belt-like (360 degrees around waist)	Triangle	
						
Measure body kinematics (IMU type)	communicates wirelessly with processor	wired to processor				
Provide feedback (tactor type)	Wired to microprocessor	Wireless				
Power system	Rechargable battery	individual battery per component	portable power pack	rechargable components (built-in battery)		
Transmit data	bluetooth	wi-fi	wired to processor			
Process data	process on body	processor on back	process off body	processor on head (hat)		
	processor around neck on necklace	processor in pocket	processor clips on waist band			
Researcher UI	laptop	smartphone				

Figure 5: Morphological chart depicting all the ideas generated for each specification-driven category. Highlighted in blue are the ideas for each sub-function that, upon group discussion, we deemed the most applicable and realistic to helping us meet our requirements and specifications.

Through the morphological chart, we observed that a total of 322,560 design concepts were generated. To identify only the reasonable design concepts, we referred to the requirements and specifications of our solution once more to select the most compliant ideas from each sub-function, in which we highlighted in blue.

IMU/Tactor Attachment Method. For the IMU and tactor attachment methods, we selected straps, bodysuit, and adhesives (stickers/tape). The three ideas adhered similarly to the requirements "wearable" and "accommodates a variety of wearers" while they distinguished themselves in the "easy to setup" and "easy to clean" categories. Also, we assessed that those three ideas were the best at securing the IMUs and tactors in place during trial to minimize shifting and rotation of those components.

Tactor Orientation. We selected the nxn grid and individual points for tactor orientation. Through interviews with stakeholders, we established specifications that the tactors must provide feedback on individual body parts as well as implicit vibrotactile feedback in the form of patterns on the torso. The nxn grid and tactors at individual points satisfy these specifications. Especially, we agreed that the nxn grid would be able to produce a more variety of feedback patterns compared to other tactor orientations.

IMU Type. For the IMU type, we selected wireless IMUs, meaning the IMUs would stream data wirelessly and have their own power source. Through our research of existing IMUs, many products—both affordable and unaffordable—had capabilities to transmit data wirelessly and have their own power source. Also, we decided that reducing the number of wires as much as possible for off-torso components would be beneficial in satisfying the specification for not obstructing the wearer's movements during trials.

Tactor Type. For the tactor type, we selected wired tactors. Since wireless tactors in the market are expensive, and wired tactors are sufficient in providing feedback, we agreed that wired tactors were adequate for this particular project. The elastic, velcro torso strap can also help to contain the wires that are associated with the tactors on the torso.

System Power. As methods to power the system, we chose rechargeable components with built-in batteries and a portable power pack. Since we decided to utilize wireless IMUs, it made most sense to individually power and recharge each component, rather than to connect them via wires along the body to a central power supply. We also found that there are IMUs commercially available that allow us to select IMUs that can be recharged or powered with a separate, single battery. To power the tactors and the processor that are connected through wires, we selected a portable power pack since having one power source on the torso rather than having batteries for each component appealed to us more in reducing weight and the obstructiveness of the device to the wearer's gait.

Data Transmission. For the data transmission method, we selected two wireless options: Bluetooth and Wi-Fi. Since we decided that the IMUs would wirelessly collect and communicate kinematic data to the processor, and the processor would wirelessly communicate with the researcher UI, the available options narrowed down to the two selected ideas, so the wearer could walk freely and not be wired to a laptop or other type of immobile processor.

Data Processing. We decided that the best location to place the processor was on the back of the wearer. The decision to select wired tactors drove the decision to place the processor on the body of the test subject as we did not want the wearer to be wired to an off-body processor during gait. Since the tactors were centered around the torso, it made the most sense to place the processor nearby to minimize any long and obtrusive wires that snaked along the wearer's body. After discussing the most strategic place for the processor that would not impede the subject's range of motion, we decided that placing it on the back was the most plausible idea. Since the processor would be on front or back of the body (as opposed to left or right side of body), it causes less impedance to the wearer through protrusion or tangled wires or by impeding arm and leg swing during gait.

Researcher UI. We agreed that laptops and smartphones were adequate for the researcher UI. We selected those two ideas because they have wireless data communication capabilities through Bluetooth or

Wi-Fi, and are powerful enough to display the kinematic data collected and transmitted from the IMUs and the on-body processor.

At this point in the concept exploration phase, we feel as if we have explored most of the solution space. By breaking down the design with a functional decomposition into sub-functions and brainstorming sub-functions individually, we were able to ensure that each sub-function was given adequate time and thought to fully gather concepts. We are currently working to further explore the solution space with providing feedback to individual body parts but also managing wires that snake along the body to reduce the obtrusiveness of the design. Our preliminary concepts include a tactor/IMU combination that is one hardware piece (we confirmed that this is available commercially without a large increase in cost) or some component that can automatically adjust for slack in wires. We are in the process of further evaluating concepts for that sub-function, so we do not formally present our results here.

By starting engineering analysis of commercially available IMUs, tactors, and processors, we were able to further explore the solution space based on what is available for our designs. We considered IMU and tactor performance specifications to help guide our sub-function brainstorming as well as our full design concept combinations (to be discussed next).

Concept Development

After refining our morphological chart by referring to our solution's specifications and requirements, we were able to narrow down the total idea combinations from 322,560 to 72. Though much lower than the original, our aim was to pursue only one idea combination, so to narrow idea combinations once more, we created our own idea evaluation tool - a concept selection tree. This tool was selected given the stage in the idea selection process we were at and the engineering analysis conducted up to that point. The concept selection tree is a way to analyze and select a full design combination from all of the generated design ideas by navigating through each category and selecting 1-2 design ideas per category until all categories are accounted for. We used the ideas that we determined to be the best for our design (highlighted in blue in Figure 5) from each sub-function in the morphological chart as the potential ideas for each category in the concept selection tree. Each row corresponds to a sub-function from the morphological chart. Each entry in the row corresponds to a top concept generated for that sub-function from the morphological chart. Since each concept in the concept selection tree was only added once the team members discussed how well that concept would meet our specifications and requirements, we are confident that any possible combination from the concept selection tree would be a viable full design concept combination. The concept selection tree method was then used to narrow full design concept combinations from 72 to 3 - this method was not used to single out an optimal idea combination because it does not incorporate design evaluation methods. The three designs that were generated using the concept selection tree method are listed below in Figure 6, denoted as designs A, B and C.

Design A		
Straps	Adhesive	Bodysuit
nxn grid	Independant points (no arrangement)	Circle
Wireless IMUs		
Tactors wired to microprocessor		
Rechargeable batteires	Portable Power Pack	
Bluetooth (IMU to researcher UI)	Wifi (IMU to researcher UI)	
Process gait information on the body of the wearer		
Laptop	Smartphone	

Design B		
Straps	Adhesive	Bodysuit
nxn grid	Independant points (no arrangement)	Circle
Wireless IMUs		
Tactors wired to microprocessor		
Rechargeable batteires	Portable Power Pack	
Bluetooth (IMU to researcher UI)	Wifi (IMU to researcher UI)	
Process gait information on the body of the wearer		
Laptop	Smartphone	

Design C		
Straps	Adhesive	Bodysuit
nxn grid	Independant points (no arrangement)	Circle
Wireless IMUs		
Tactors wired to microprocessor		
Rechargeable batteires	Portable Power Pack	
Bluetooth (IMU to researcher UI)	Wifi (IMU to researcher UI)	
Process gait information on the body of the wearer		
Laptop	Smartphone	

Figure 6: Concept selection trees for Designs A (top), B (middle), and C (bottom). Cells highlighted in green are selected idea combination paths.

The concept selection tree gives us more confidence that we are close to fully exploring the solution space. We had many full concepts to evaluate, and the concept selection tree allowed us to look at many different full design concept combinations that would be feasible. Based on our initial engineering analysis, we are confident that there are components available commercially that would allow us to prototype any of these full design concepts. We are still looking at potential components, but once we complete the evaluation of commercially available components (IMUs, tactors, processors, power sources), we can be confident that we have fully explored the solution space. The resulting designs from our concept selection tree are explained below.

Design A

Design A showcases the following features: it incorporates elastic straps with velcro for IMU attachment to the head, left or right wrist, both legs, and the lower-back to device wearers, an n-by-n tactor sleeve that will wrap around the lower trunk of device wearers with elastic and velcro for proper fitting, and individual tactors attached with adhesives to the head, left or right wrist, and both calves of device wearers. All tactors and IMUs will be wired directly to a power pack for power supply. The tactors will be wired to a processor for communication of a feedback scheme while the utilized IMUs will establish wireless communication with the processor. The processor will communicate with the researcher interface through Wi-Fi for the researcher settings, and, if applicable, transfer of essential gait information and feedback information for the device wearer. Finally, the selected researcher user interface will be a laptop. These idea selections are compiled succinctly in Figure 7 below.

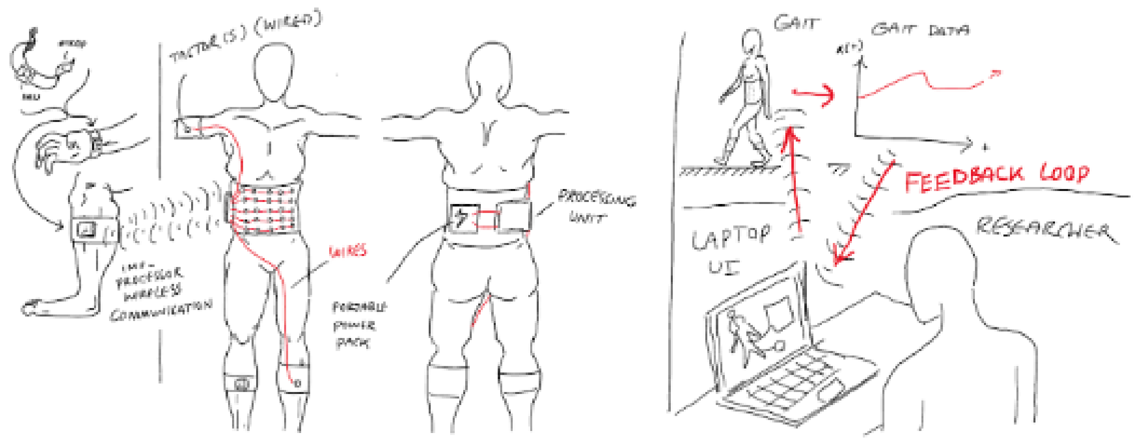


Figure 7: Conceptual drawing of Design A.

Some pros to this design are that the power pack ideally would have a long battery life, the tactors will provide ample feedback directly to specific body parts, and the device will be easily adjustable for different people. Some cons are that there may be a longer range requirement for processor-laptop communication and the adhesives used to attach the tactors may be hard to clean/not reusable.

Design B

Design B showcases the following features: it uses a body suit for IMU attachment to the head, left or right wrist, both legs, and lower back of device wearers. The body suit also allows for tactor attachment, utilizing the same n-by-n tactor array for the lower trunk and incorporating individual tactors located at the head, left or right wrist, and both calves of device wearers. All tactors will be wired directly to the processor for power supply and actuation while the utilized IMUs will establish wireless communication with the processor and will be powered by individual rechargeable batteries. The processor will communicate with the researcher user interface through Bluetooth for the researcher settings, and, if applicable, the transfer of essential gait information for the researcher and feedback information for the device wearer. Finally, the selected researcher user interface will be a smartphone. These idea selections are compiled succinctly in Figure 8 below.

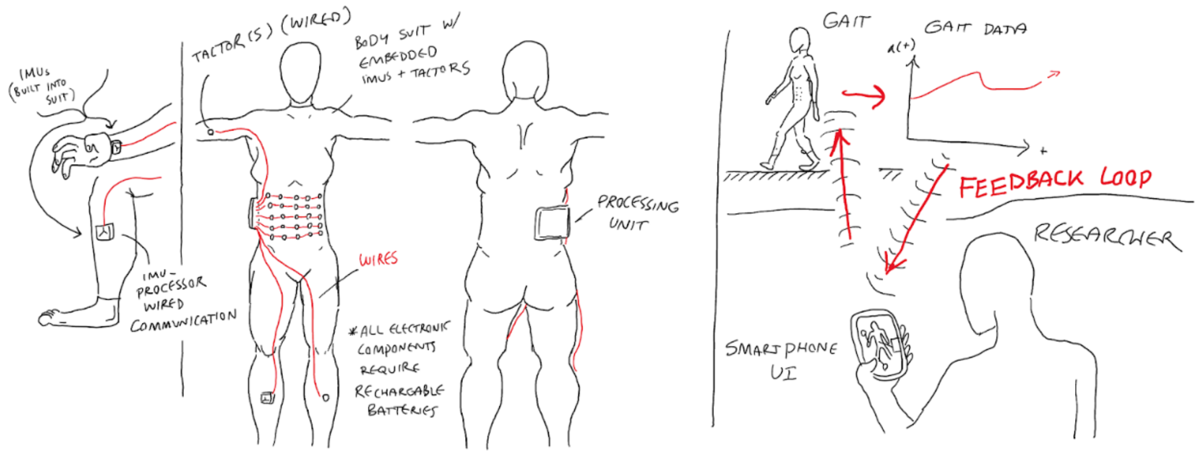


Figure 8: Conceptual drawing of Design B.

Some pros to this design are that the body suit is a more consistent way to keep IMUs/tactors in ideal positions and the device would be easy to assemble. Some cons with this design are that the body suit may be difficult to adjust for different sizes as well as be difficult to clean, and that having individual batteries may result in long down-times to replace/charge them.

Design C

Design C showcases the following features: it utilizes adhesive to attach IMUs directly to the head, left or right wrist, both legs, and the lower-back of device wearers. Tactors are arranged in a circular formation and are attached to the trunk of device wearers through a sleeve with elastic and velcro. Individual tactors will also be located at the head, left or right wrist, and both calves of device wearers. All tactors and IMUs will be wired directly to a power pack for power supply. The tactors will be wired to the processor for communication of the feedback scheme while the utilized IMUs will establish wireless communication with the processor. The processor will communicate with the researcher user interface through Bluetooth for the researcher settings, and, if applicable, for the transfer of essential gait information for the researcher and feedback information for the device wearer. Finally, the selected researcher user interface will be a smartphone. These idea selections are compiled succinctly in Figure 9 below.

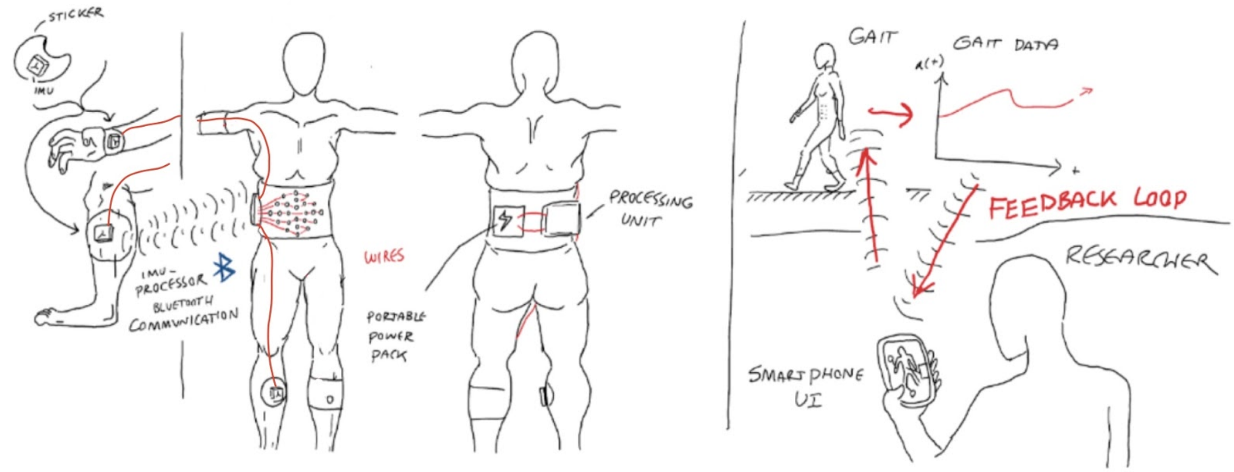


Figure 9: Conceptual drawing of Design C.

Some pros of this design are that it mitigates component movement, accommodates a variety of sizes, and is easy to put on. Some cons of this design are that adhesives are not reusable/cleanable, and repeatable precise placement is not plausible.

Given that we wanted to move forward with one design, our aim was to have a standardized way to evaluate our three idea combinations (Designs A, B, and C). This standardized approach is discussed in the following section.

Concept Evaluation/Selection

To evaluate the three concepts (design A, design B, design C), we used a decision matrix (Table 4) where the categories were determined based on sub-sections for our requirements and specifications. Specifically, we focused more so on the physical aspects of the design/our requirements and specifications as we wanted to still focus on the needs of our stakeholders but also straying away from things such as the UI and the processing power of our design so that we weren't limited for future endeavors. Through this decision matrix, we saw how well each design was rated as a whole and how each design concept compared to the others, and, at the end, we were able to determine both the highest rated design and identify sub-components of our designs that were highly rated that could be incorporated into a final, cumulative design.

Categories were unweighted because we deemed all categories equally necessary for a successful design. For each category, each design was given a 1, 2, or 3 rating, where a 1 indicated the design was bad at meeting the category, a 2 indicated the design was okay at meeting the category, and a 3 indicated the design was good at meeting the category. Using a good/okay/bad rating scheme allowed us to rate the designs fairly by how we thought they objectively fit each category as opposed to purely comparing their functionality to each other. Discussion on how each rating was determined is provided after Table 4. All group members discussed and collaborated on each rating until a consensus was reached.

For each stakeholder requirement, we considered adding a category to the decision matrix. There were a number of requirements that were met by each of the three designs and were crucial to the device functionality. These requirements were not included as categories in the decision matrix because the three designs met the requirements in similar ways. For example, all three designs have the tactors, the processor, and, if applicable, the power pack distributed symmetrically around the trunk and the IMUs in the same five locations (head, legs, lower back, wrist). The specifications regarding the vibration frequency, signal processing, range of connection between the processor and laptop, and the battery life of the system depend on the specific hardware for the design, so they were not included as categories in the decision matrix since they are design independent.

We also did not include the lower priority requirements ("expandable to accommodate different modes of feedback" and "accommodate additional kinematic data sources") as categories in the decision matrix because those requirements are primarily for future project iterations. We reserved those requirements to compare two similar scoring designs, if applicable. As can be seen in figure 4, one design significantly outscored the other two designs, so we did not consider the lower priority requirements in our concept selection.

Table 4: The decision matrix used to evaluate three concepts and determine a selected concept. The ratings of 1, 2, and 3 correspond to how bad, okay, and good the design is at meeting the specific category.

Category	Design A	Design B	Design C
Accommodates a variety of sizes/people	3	1	3
Provides semi-real time feedback	3	3	2
Easy to clean	3	1	1
Reusable/re-wearable	3	3	1
Easy to Set up/put on	3	2	3
Measures data without shifting on the body between trials	2	3	3
Doesn't impede motion while walking	2	2	2
	19	15	15

Accommodates a variety of sizes/people. This category came from the requirement "design accommodates a variety of wearers". Design A and Design C both incorporate adhesive and velcro straps to attach IMUs and tactors. Design B uses a bodysuit with built in IMUs and tactors. Straps can be one-size-fits-all as they can be easily made in multiple lengths (according to our specifications), and the adhesives can secure components to the body without regard for any bodily measurements, so Design A and Design C were considered good in this category. The bodysuit would need to account for additional body measurements and may need multiple designs to accommodate different sizes (small, medium, large), so design B was considered bad for this category.

Provides semi-real time feedback. This category combined the "semi-real time feedback" and "vibrotactile feedback display" requirements. All three designs provide vibrotactile feedback to the wearer during the trial in the form of an array on the torso. Design A and Design B also allow vibrotactile feedback to be provided to individual body parts (head, wrist, legs) as well as an array on the trunk, allowing for both explicit and implicit feedback. This is why those designs were rated good. Since design C is limited to the tactor array on the trunk, the design was rated as okay.

Easy to clean. The easy to clean category was taken directly from the "easy to clean" requirement. For all three designs the hardware must be removed from any material that can be washed with water and detergent. Since this step is a step required to clean each design, we did not rate any designs higher or lower for requiring this step. Instead, we considered the ease of cleaning non-hardware components of the design, since all of the hardware components will have the same ease of cleaning. For design B, the body suit got a bad mark for this category since the entire body suit would need to be cleaned with water and detergent which could limit the number of test sessions done per day since the body suit is large and would take a longer time to clean. For design A, IMUs and tactors are attached with elastic, velcro straps that can easily be cleaned with water and detergent, so design A is good for this category. Straps are smaller than the body suit so the straps can be cleaned quicker, and, hence, they can be used more frequently for test sessions. For design C, the IMUs are attached to the body with adhesive, and tactors are attached to the body with an elastic, velcro strap. The adhesives, being the largest part of this design, cannot be cleaned, so design C was bad for this category.

Reusable/re-wearable. The reusable/re-wearable category was also based on the "easy to clean" requirement. Design A and design B have attachment methods that can be cleaned and reused with other wearers, so they were rated good. Design C requires new adhesive for each wearer, so design C was rated bad.

Easy to set up/put on. This category came from the "easy to setup" requirement. All designs require the IMUs and tactors to be placed in the proper location. Design A involves straps that can be strapped onto the various body parts consistently, so design A was rated as good. Design C involves the same strap design and also adhesive that can easily be placed onto the various body parts, so design C was also rated as good. Design B was rated as okay because the body suit can be difficult to put on considering the wide expanse of material it has.

Measures data without shifting on the body between trials. This category came from the "wearable" requirement. Design B uses the body suit, which would keep all of the tactors and IMUs in place if the body suit was sized correctly, so design B was good for this category. Design C uses adhesives for the IMUs and tactors. Using adhesive that was strong enough, design C would be good for this category since the IMUs and tactors would be stuck in place. Design A was okay because the straps ensure that the IMUs and tactors do not fall off, but the straps may not easily stop the components from shifting around the body part they are strapped to.

Does not impede motion when walking. This category came from the "wearable" requirement. Design A has individual tactors located at the head, legs, and wrist that are wired to the processor and power pack located on the wearer's back as well as IMUs around the body that would also be wired to said power pack. The slack in the wires would need to be perfect as if they are too loose, it might hit the wearer's limbs and interfere with their body motion, but if they are too tight, the wires could provide resistance to the wearer and impede their body motion in that way. Therefore, design A was rated as okay. Design B was rated as okay because if the body suit does not fit well (could be too large or too small), body motion may be affected. For design C, tactor wires are contained in the elastic, torso strap since there are no tactors at individual body segments. The IMUs are strapped to the body, but similar to design A would be wired to the power pack. Therefore, Design C was also rated as okay.

Based on these ratings for each category, design A was the highest scoring concept, scoring a 19 out of a possible 21. Supporting this rating, of the three designs, design A was the only design that was ranked good or okay for all categories, indicating that there is a high likelihood that design A will meet our specifications and requirements that are independent of the hardware. Design B and design C both had numerous categories that they scored bad in, meaning we didn't have as much confidence in these designs going forward. Design A formed the basis for the selected concept, but through the decision matrix we also identified ways that we could improve design A. Our selected concept uses adhesive to attach an IMU to the lower back, instead of a strap like in the original design A. This will help reduce the chance of that IMU from shifting around the body during trials since the IMU will be independent of the large torso strap. To eliminate the wires stretching from the power back on the back to each limb with an IMU, we also determined that incorporating rechargeable IMUs into design A would help prevent the device from impeding motion when the wearer is walking.

Selected Concept

Based on the concept selection process described in the previous section, our team chose to pursue Design A. Figure 10 displays our detailed sketch of Design A. To fully explain our design, we will use the sub-functions and categories of the functional decomposition tree (Figure 4). These breakdowns of the functional decomposition can be seen in Figures 11, 13, 15, and 17.

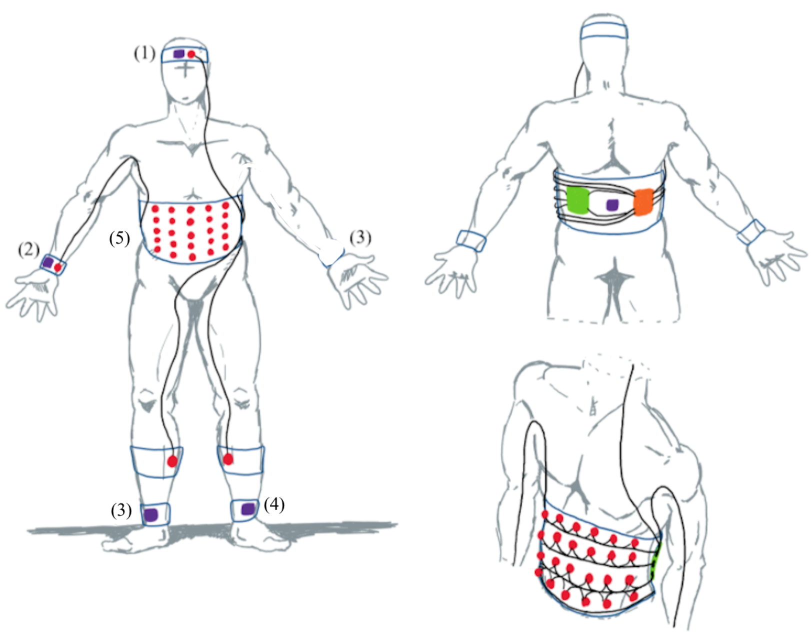


Figure 10: Detailed concept sketch of Design A. This sketch showcases how each piece of the design works together to gather data, process data, and provide feedback to the wearer while they are walking.

Figure 11 displays our IMUs category of our functional decomposition. It is important to note that in the image we have indicated we will use MTR Metatracker (pending) for our IMU type. However, we are still in the process of selecting an IMU and so this is not set. We are planning to use a decision matrix based around the available specs of multiple IMUs to make our final decision (more details in Next Steps). The MTR Metatrack is just one IMU that we found to be commercially available that would allow the selected design to be feasible. The IMUs on the head, legs, and wrist will be attached to the body using elastic straps that use velcro to readjust sizing for each wearer. Adhesives will be used to attach an IMU to the wearer's lower back. For now, we have indicated that the IMUs will transmit information for processing via Bluetooth connection and will be powered via disposable battery. The Bluetooth connection is subject to change depending on the capabilities of the IMU type we select in our decision matrix. There are some IMUs that are available commercially that allow data transmission over Wi-Fi, and also some that can be recharged as opposed to having a disposable battery. Additionally, a most recent interview with our stakeholders revealed that they would prefer a rechargeable IMU that indicates its power level. Therefore, a disposable battery is no longer a preferred option, and the Power Supply sub-function may change. Additional sketches specific to this branch are displayed below (Figure 12).

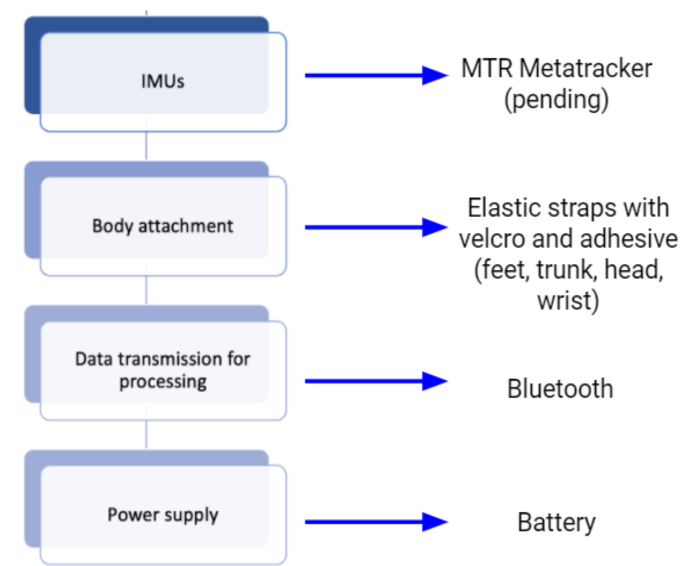


Figure 11: Functional Decomposition, IMU branch. The IMU Type, Data transmission, and Power supply sub-functions may change depending on the IMUs selected in our decision Matrix.

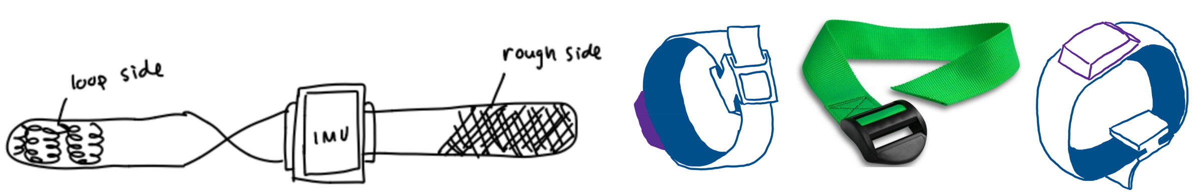


Figure 12. Additional sketches of the IMU component. IMUs will be attached to an elastic strap and the strap length adjusts with velcro.

Figure 13 displays our Tactors category of our functional decomposition. Similar to the IMU sub-functions, the Tactor sub-function lists a VPM2 Vibrating Disk Motor (pending), but may change depending on the results of our Tactor decision matrix (more details in Next Steps). This was just one example of an affordable, commercially available tactor that allowed the selected design to be feasible. We plan to attach our tactor arrays to the body using elastic straps with velcro to adjust sizing. Additionally, if our stakeholders want to apply vibrotactile feedback to individual body parts, we will use adhesives to attach these tactors. This is reiterated in the "Orientation" sub-function, where our stakeholders will be able to arrange the tactors in an n x n grid on the trunk of the body as well as on individual points. The tactors' subsystem will be powered by a portable power pack and may be wired to the processor. The wired tactors were chosen because most tactors we found required physical wires. However, we plan to explore this feature again, as our stakeholders noted that tactors wired from different body locations may limit the motion of the wearer. Additional sketches specific to this branch are displayed below (Figure 14).

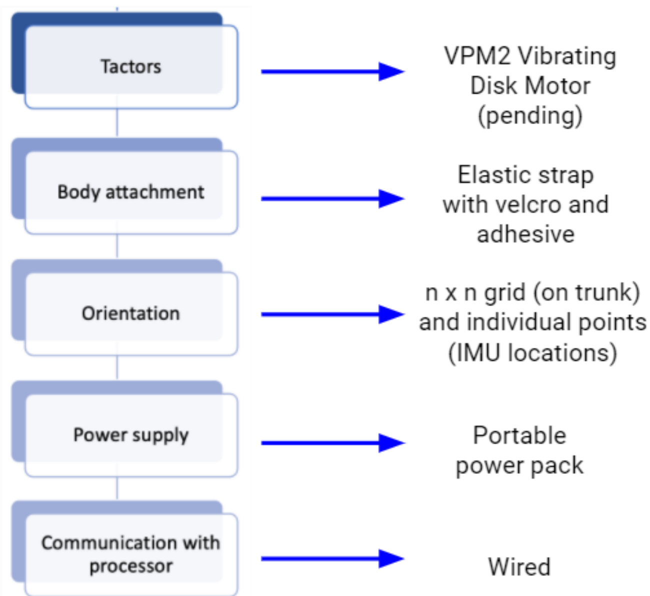


Figure 13: Functional Decomposition, Tactors branch. The Tactor type and Communication with processor sub-functions are subject to change depending on the Tactors selected in our decision matrix

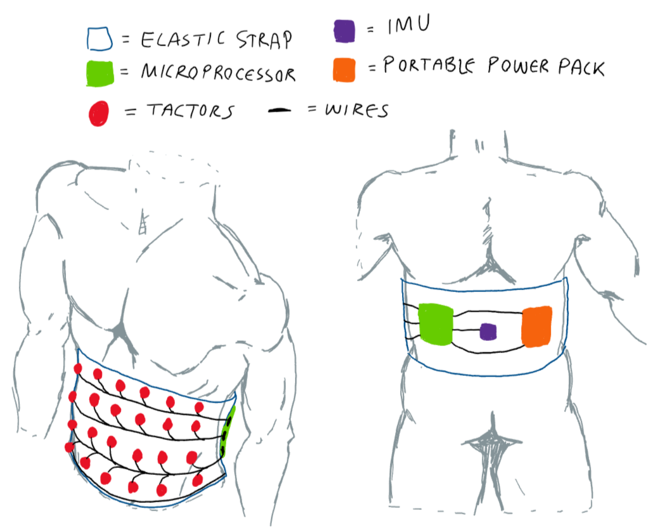


Figure 14. Additional sketches of the tactor component. An elastic band attaches the tactors to the wearer's torso in an n x n grid. A portable power pack will be attached to the back of this elastic band.

Figure 15 displays our Processor category of our functional decomposition. We are currently planning to use a microprocessor, potentially an Arduino Uno R3, that is attached to the lower back using the same elastic strap that attaches the tactor array to the trunk. The specific processor that we use will be finalized with a decision matrix, and will be somewhat dependent on the IMUs we pick to ensure that they will be able to communicate wireless. We chose to use a microprocessor on the body because the IMUs and tactors we saw in our research had a limited range that would not span the 35m required in our specifications. By adding a microprocessor to the body, these sensors and tactors could communicate with the processor at a shorter range, and then this processor could be used to communicate with the researcher user interface at a longer range. We plan to have the microprocessor communicate with the IMUs, though this will depend on the capabilities of the IMUs we select. The tactors may be wired to the processor, but further exploration into available tactors may change this. Finally, the settings set by the researchers will be interpreted and stored on the processor through code. Additional sketches specific to this branch are displayed below (Figure 16).

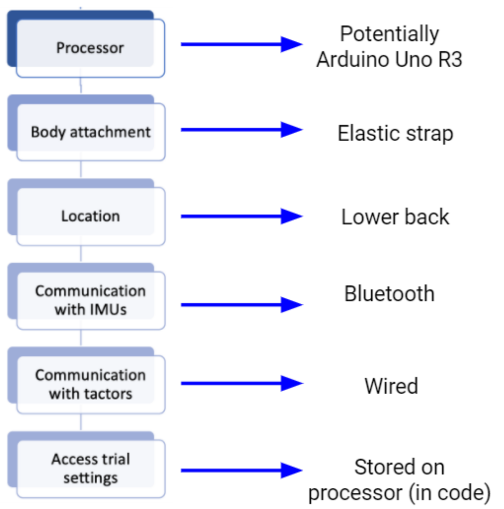


Figure 15: Functional Decomposition, Processor branch. The Processor type and Communication with IMUs/tactors are subject to change depending on the processor, IMUs and tactors selected in our decision matrix.

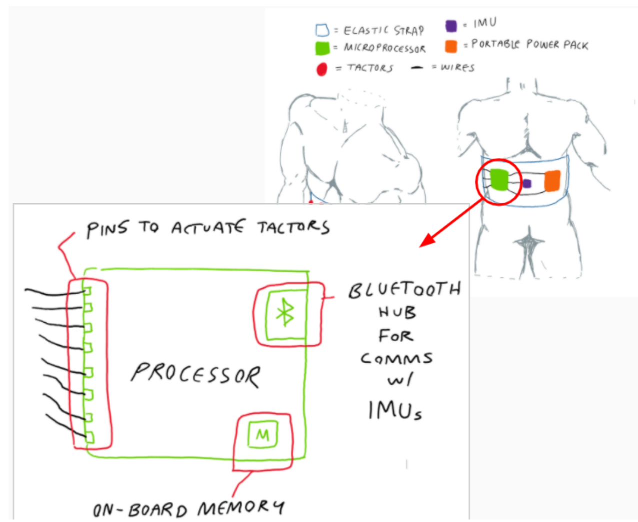


Figure 16: Additional sketch of the processor component. The processor will be located on the wearer's lower back by attaching to the same elastic band that holds the tactors and portable power pack.

Our final branch, Researcher User Interface (UI) is shown in Figure 17. We plan to use a laptop, as opposed to a smartphone, as the platform for the Researcher UI. This is because information is easier to view on a larger screen, it is easier to edit the processor's code/settings directly using a laptop, and there is more flexibility with analysis of the IMU data. As mentioned previously, the researcher UI will communicate with the processor on the wearer's body via Bluetooth to allow for a wireless connection. The trial settings chosen by the researchers will be stored in code on the processor.

To ensure that our design fulfills our stakeholders' needs, we cross-referenced our design with the project requirements and specifications (Table 3). For the "Wearable" requirement, we plan to use lightweight components in our design to ensure the total weight of the device is <2.5kg and will be securely attaching the device to the wearer via straps and adhesives to ensure it does not fall off during each trial.

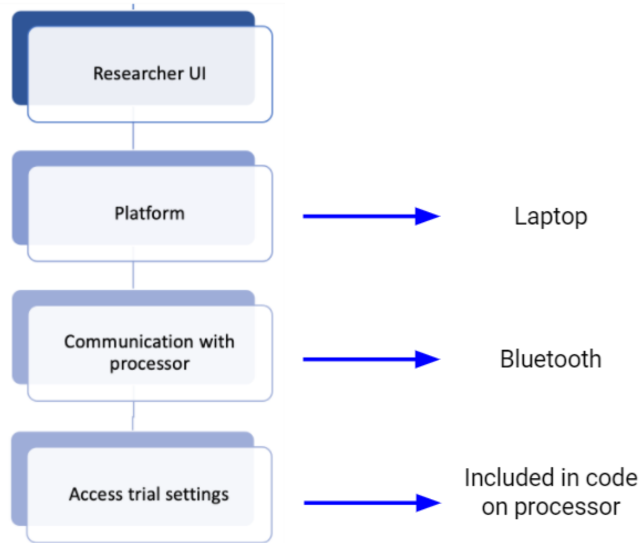


Figure 17: Functional Decomposition, Researcher User Interface branch. Communicate with processor is subject to change depending on the processor selected in our Design Matrix.

For the "Accommodates a variety of wearers" requirement, we will have strap dimensions that are large enough to fit the largest head, waist, calf, and wrist sizes listed in our specifications, but are adjustable with velcro so that wearers with smaller dimensions can also wear design securely. These dimensions are listed in Table 5 below.

Table 5: Maximum and minimum strap size adjustments for Design A. These dimensions are from head, waist, calf, and wrist specifications found in Requirements and Specifications table (Table 3)

	Head	Waist	Calf	Wrist
Maximum Size Adjustment (cm)	60.0	132.6	47.1	19.1
Minimum Size Adjustment (cm)	51.9	73.3	31.8	13.8

For "Semi-real time feedback" and "Kinematic data measurements," we are looking at different IMUs to ensure that they have the appropriate sampling rate required to track body motion and supply this info to our processor in a timely fashion. We are also looking at different tactors to ensure that their size and vibration frequencies provide the wearer with detectable vibrotactile feedback. Additionally, we are adding a microprocessor to increase the range of connection between the sensors and researcher user interface.

To meet the requirement "Vibrotactile feedback display", we've made sure that our design includes tactors located on each of the body locations listed in our specification.

For "Interactive researcher interface", we are looking for sensors that are compatible or come with software packages that allow for an interactive researcher interface via a laptop, which can also save user settings and be reused between sessions to fulfill “Easy to Set Up”. For “Easy to Clean,” straps for our IMUs will be made of a washable material, and the adhesives for the tactors will likely be disposable.

Our last two requirements (“Expandable to accommodate different modes of feedback” and “Accommodate additional kinematic data sources”) are ranked as low priority because they are meant for future variations of the device, and are not necessarily critical to our first design iteration. Given this, and the fact that we did not need to use these requirements as a tiebreaker between design concepts (reference Concept Selection) we did not focus on cross-comparing our design to these specifications. We did not want these features to limit our design if it fulfilled our main requirements.

Concept Evolution

Since selecting one concept to move forward with, our selected design concept (denoted design concept A in previous sections of this report) has been ratified according to further conducted engineering analyses.

Notable changes include (but are not limited to):

- The location of the IMUs that were originally on the shanks of the device wearer have been moved to the ankles.
- The circuit design for activating tactors individually and wire management for all electronic components on the device was further developed.
- The IMUs will be attached to the body with velcro straps, pouches, and a beanie instead of adhesive.
- The breadboard will be included on the torso as well as a number of other components.

The location of the IMUs for lower-body gait data collection was changed from the shanks to the lower leg (ankle) of the device wearer for easier attachment. This was changed because it was difficult to have an IMU stay in place with straps in the middle of a person’s lower leg. The strap had a potential to slide down the leg or rotate if the two legs came into contact with each other. Putting the IMU on the ankle allowed the IMU to be held in place more securely. The strap cannot slide down the leg since the strap is located at the bottom of the leg and there is less of a chance that the wearer’s ankles will come into contact with each other to rotate the strap. This change is shown in Figure 18. The leg tactor location has not changed. They will still be strapped onto the calf. This location was not changed because the vibrations were easier felt on the calf than around the ankle. We anticipate having to strap the tactors on tightly, but due to the lighter weight of the tactors compared to the IMUs, we do not anticipate the straps sliding significantly.

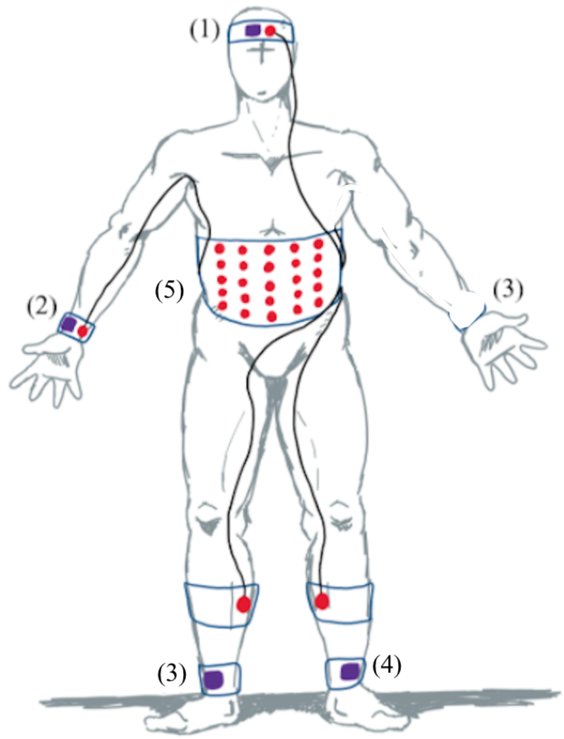


Figure 18: Final design concept showcasing concept evolution. Tactors are shown in red. IMUs are shown in purple. IMU 5 is not visible as it is located on the lower back.

The circuit design and wire management for all electronic components on the device originally called for all tactors to be in parallel series pairs (i.e. two tactors at a time are in series while all fifteen tactor pairs are in parallel) and wires were meant to be mounted to retractable spools to ensure the device wearer's gait was not obstructed. The circuit design was built upon after empirical testing was conducted - the team discovered that to have the capability of activating individual tactors and/or tactors synchronously, each tactor would have to have its own communication channel. This led to the inclusion of a number of transistors in the circuit design, making all tactors singular and in parallel. In regards to the original wire management scheme, the team met with their stakeholders and discussed the validity of this method. As a result of this conversation, this method was tabled for time concerns, and at this stage, the team plans to use tape or adhesive to attach wires to areas of the device wearer that will not obstruct their gait, and preserve the slack of the wires while in motion.

The design for the IMU attachment methods have also been updated. We will primarily be using velcro straps and 3D printed holders instead of adhesive. For the IMUs, we will purchase straps that are within our length requirements and also have a built in pouch for the IMUs on each leg and the IMU on the wrist. The straps will still attach with velcro. For the head IMU, we will purchase a beanie and 3D print an IMU holder that will attach to the front of the beanie. The lower back IMU will also have a 3D printed holder that will hook onto the torso strap. If any of the IMU pouches result in excess IMU movement, we plan to use foam to hold the IMU in place.

The last notable change in our design is that the back of the torso strap will house the breadboard (neglected in the original design) and any other components needed on the wearer (including power supplies, processor, etc.). There will be individual pouches (made out of the same elastic material as the strap) that will be sewn onto the back of the strap so that the weight is distributed evenly and the components do not impede with the wearer's arm or leg swing.

Design Drivers

To ensure functionality of our design, we created a list of 7 design drivers. These drivers are listed below in Table 6, along with a list of engineering analysis procedures we believed would be most effective in answering their corresponding driver. Any engineering analysis written in green text indicates that it has been completed, whereas red text indicates that we are still in the process of conducting it.

Table 6: Design drivers to guide solution development. Design drivers are prioritized in descending order. Engineering analysis in green indicates a completed process, and engineering analysis in red represents analysis in progress.

#	Design Driver	Engineering Analysis
1	Are there IMUs, processors, and tactors that are capable of measuring kinematic motion, streaming information from 5 sources for post-processing, and activating 30 tactors around the body that are **commercially available** for a **reasonable price** that we can integrate into our design in **one month**?	• Product assessment: IMUs, tactors, processors
2	How can we set connection parameters so that the IMUs communicate with the processor over Bluetooth in a timely manner without loss of data?	• Product assessment: IMUs, processors • Empirical/Prototyping: IMU calibration & communication with processor via Bluetooth
3	How can we configure our processor to **store, send, and receive information to the researcher interface in a timely manner** and **integrate** into our design **in one month**?	• Product assessment: processors, IMUs • Subsystem prototyping: IMU and researcher UI configuration • Subsystem prototyping: tactor and researcher UI configuration
4	How can we manipulate tactor activation (both in the 5x5 array on the torso as well as those at individual points around the body)?	• Online documentation • Theoretical: circuit schematic • Empirical/Prototyping: Purchase cheap tactors and integrate one by one • Empirical/Prototyping: Tactor activation with h-bridges and/or transistor arrays

#	Design Driver	Engineering Analysis
5	How can we configure our processor to **receive information** from 5 IMUs (leg, wrist, lower back, head) and **send information** to 30 tactors around the body (5x5 array on torso, head, calf) and **integrate** into our design **in one month**?	• Product assessment: processors, IMUs • Theoretical: circuit schematic • Empirical: IMU configuration • Empirical: Tactor configuration
6	How much power is sufficient to activate a 5x5 grid of tactors?	• Research power consumption specs for tactors and online documentation; • Equations to determine power supply/power consumption requirements
7	How much power is sufficient to activate 5 individual tactors around the body?	• Research power consumption specs for tactors and online documentation; • Equations to determine power supply/power consumption requirements (signal processing)

The engineering drivers are listed in descending order of priority, related to the function of the design. Design driver #1 relates to the commercial availability of IMUs, tactors, and processors which can appropriately measure kinematic body motion, process this data, and administer the appropriate vibrotactile biofeedback to the wearer. This was considered our top priority because, due to time constraints, budget, and lack of experience, we would be unable to assemble the design without having components available for purchase. Design driver #2 relates to the speed and amount of data transferred between the IMU and the processor. This is ranked as second, because any loss of data or significant delays in communication can prevent the device from providing appropriate feedback on the wearer's gait within the trial, which is the main goal of our project. Design drivers #3 and 5 address the communication between the processor, IMUs, tactors, and researcher user interface. The compatibility of our sensors are important, because even if each component works individually, wearers cannot receive biofeedback on their gait if all components do not communicate with each other appropriately. Design driver #4 addresses the ability of the researchers to activate various tactors. As this device is for research purposes, the researchers must be able to adjust tactor activation so they can experiment with different vibrotactile feedback patterns. Design drivers #5 and 6 discuss the power requirements for each tactor setup so that we can purchase the appropriate power supply for our design. This was ranked last, because it does not relate to **how** the design functions, though it is still necessary for our design to function at all.

Each engineering design driver listed in Table 6 will be further explained in the following sections, along with our justification for why each engineering analysis procedure was used. Based on our engineering analysis, we are confident we have demonstrated proof of concept for our design since our design drivers reflect all of the main sub-functions for a successful design (i.e. streaming and receiving data, activating different tactors, processing researcher settings, saving all data, etc.). Any engineering analysis procedures that we did not conduct during this phase were completed during Verification.

Design Driver #1

The first design driver addressed component selection for IMUs, tactors, and a processor. We wanted to select commercially available components that satisfied our requirements and specifications and were compatible with each other. To answer this question we generated decision matrices for the IMUs and the processor. We generated a specifications chart, and purchased two types of tactors for empirical testing before deciding on which tactor to go forward with for the final design.

IMU Selection

To select appropriate IMUs for our selected design concept we generated a decision matrix shown in Figure 19. The four IMUs we considered were the Xsens DOT, the Mbientlab MMRL, the MbientLab MTR Metatracker, and the LPMS-B2.

Weight	Category	Spec Range	Xsens Dot		MMRL		MTR Metatracker		LPMS - B2	
2	Size	(< 33.2 mm height)	0	10.8 mm	0	10 mm	0	15 mm	0	8 mm
2	Weight (g)	Less is better	0	10.8 g	0	8.5 g	-1	19.8 g	0	12 g
3	Battery Life	(> 2hr)	0	6 hours (continuous use)	0	8 hours (streaming)	1	14 - 75 days	0	6 hours
3	Battery Type	Rechargeable	0	rechargeable	0	rechargeable	-2	coin cell battery	0	rechargable
2	Built-In Battery Life Indicator	Yes/No	0	Yes; LED	-1	No	-1	No	-1	No
2	Range	(> 2 m)	0	BLE	0	BLE (10 m)	0	BLE (10-30 m)	0	BLE (< 20 m)
4	Simultaneous Connections	≥ 5	0	5 for BLE	0	5 for BLE	0	5 for BLE	0	5 for BLE
4	Gyroscope Range (degree/sec)	(≥ ±1000 deg/s)	0	2000 deg/s	0	2000 deg/s	0	2000 deg/sec	0	2000 deg/s
4	Accelerometer Range(g)	(≥ ±16g)	0	16g	0	16g	0	16g	0	16g
4	Sampling Rate	100 Hz	0	800 Hz (no excess data)	0	100 Hz	0	100 Hz	-1	400 Hz (excess data)
3	Cleanable	Yes/No	0	yes	0	yes	0	yes	0	Yes
1	Price	Less is better	0	$105	1	$83.99	2	$60.99	-2	$249
4	Documentation/Libraries	More is better	0	Xsens DOT educational download; bluetooth documentation; base education database	-1	Tutorials and APIs available in many languages	-1	MetaWear APIs	1	C++ documentation widely available online, help wiki available for Open Motion Analysis Toolkit (OpenMAT)
3	Streaming Rate	Faster is better	0	up to 60 Hz	1	100 Hz	1	100 Hz	2	up to 400 Hz
2	Lead Time	<1 week	0	Ships within 10 days	1	ships in 2-3 days	1	ships in 2-3 days	-2	available 3/15
2	Additional Equipment	Less is better	0	charger	0	charger	-1	replacement batteries	1	none
1	Strap/Adhesive Availability	Yes/No	0	Yes	0	Yes	0	Yes	-1	No
	Total		0		0		-6		-1	

Figure 19: Design matrix for IMU selection

We determined each category in the decision matrix by referring to our requirements and specifications. We assigned different weights to each category according to its importance. The weights range from 1 to 4, where 4 indicates the most important category. Each category is rated from -2 to 2, where 2 is the highest rating. The ratings are given relative to the Xsens DOT, but also with consideration to the specification range since some of the IMU specifications were all very similar relative to the specification range. The justifications for selecting each category and specification range are listed below:

Size. The average human arm length is 63.5 cm, and the movement of the shoulder during normal gait is 3-12 degrees in the frontal plane. After calculations [33], we determined that the maximum protrusion of the device should be limited to 33.2 mm. While size of IMUs is important to prevent interfering with gait, all IMUs were comparable in size and small, we did not anticipate having problems reaching our specification range so this was given a lower weight.

Weight. From our research, reflected in our requirements and specifications, the weight of our design needs to be below 2.5 kg to not affect the gait of the wearer. Therefore, to help meet this specification, a lighter IMU is preferred. The individual weight of IMUs is somewhat important, but since they are all around the same weight and will be placed at different parts of the body, we will not get a concentrated weight so this category was given a lower weight.

Battery Life. Our stakeholders expressed that the sessions they will run with the design would be, at most, 2 hours long. Therefore, as we do not want any adjustments to be done in the middle of any sessions/trials, we need the battery life to be greater than 2 hours long. Battery life was given a higher weight because it is important to last the entire length of a trial.

Battery Type. Stakeholders expressed interest in a rechargeable IMU. If the IMU used a battery that could not be recharged, the researcher would have to remember to order new batteries and replace the battery. This was given a higher weight because any battery that must be replaced frequently is an inconvenience and could potentially stop trials while batteries are ordered.

Built-In Battery Life Indicator. To ensure that an IMU did not run out of battery during a session, we wanted an IMU with a built-in battery life indicator. We did not want the researcher to have to measure the voltage of a single-use battery to have an indication of the battery life. Some of the rechargeable IMUs we found had a light that functioned as a built-in battery life indicator. While this was nice to have, it was not required so the weight of this category is lower.

Range. The range is a measure of the distance between an IMU and the processor. The IMU must transmit data wirelessly to the processor for processing. With the IMUs located on the head, leg, lower back, and wrist and the processor located on the lower back, the IMUs will be within 2 m of the processor, so the IMU must be able to transmit data > 2 m to ensure data transmission can occur. Range is important for a functioning product, but since the specification range is so low relative to IMU capabilities, this was given a lower weight.

Simultaneous Connections. We are connecting the IMUs wirelessly over Bluetooth to the processor to transmit data, so the maximum number of BLE real-time streaming of data transmitting devices is 7, but for increased performance the maximum is 5 devices. Since we do not intend to use any of the commercially available software from Xsens or MbientLab, we were not concerned with the number of devices that could simultaneously connect to the app. The Xsens DOT and the MbientLab IMUs are both factory calibrated, so we don’t anticipate any reason to need the available software for all IMUs simultaneously. To fully track gait motion our design needs to have at least 5 simultaneously connected streaming devices, so this was given a high weight.

Gyroscope Range. The IMU gyroscope collects information on angular velocity. Combined with the acceleration data collected from the IMU accelerometer, orientation and displacement data can be found. The IMU gyroscope must be able to capture the full angular velocity of the head, torso, legs, and wrist.

Out of these body segments, the leg will have the largest peak angular velocity, which is no higher than 1000 deg/s [44]. Thus, we are searching for IMUs with gyroscope range of at least ±1000 deg/s. Note that this was originally listed as 2000 deg/s, based on benchmarking/sensors used by other gait studies [43], but it was lowered to better reflect the mechanics of gait. This was given a high weight since a sufficient gyroscope range is necessary to accurately track gait.

Acceleration Range. The IMU accelerometer collects information on acceleration. Combined with the angular velocity data collected from the IMU gyroscope, orientation and displacement data can be found. A study was conducted to determine what IMU features are important to consider for gait analysis research [43]. After testing several IMUs, the peak acceleration in the raw data was cut off for IMUs with accelerometer ranges less than ±16g. It was concluded that the loss of the peak acceleration data led to inaccurate movement trajectory estimation/shorter estimation of stride lengths. To ensure that our IMUs can collect all critical acceleration data, the accelerometer must have a range of at least ±16g. This was given a high weight since a sufficient acceleration range is necessary to accurately track gait.

Sampling Rate. According to existing studies, IMUs operating at 100 Hz is sufficient for capturing daily life activities such as walking or picking up objects [43]. Since we do not want excess data that would potentially slow down our data processing, we will search for IMUs that are functional at 100 Hz. While the Xsens DOT is not able to sample at 100 Hz, there is internal processing that will condense the data while still preserving key features. Based on our research, the Xsens DOT will not result in excess data while in streaming mode since the data will automatically be condensed for optimized streaming time. Sampling rate was given a high weight because a sufficient sampling rate is necessary to accurately track gait, but we also do not want to slow down our data processing with excess data.

Cleanable. According to our stakeholders, due to current safety issues the researchers only take one test subject per day, so the need to clean the device between trials is not a concern. They expressed that they wanted the fabric portion to be launderable and the electronic portion to be wiped with disinfecting wipes. This was given a higher weight because of potential hygiene concerns.

Price. Our original rough budget for this project was $400, however our stakeholders informed us that we may need to go beyond this to obtain the appropriate components required for the design, so the weight was low for this category. To be as close to the original budget as possible, we prefer our IMUs to be as cost effective as possible. However, we still have to make sure that our IMU meets our other requirements which are more important than price.

Documentation/Libraries. Documentation/libraries vary per IMU utilized. Some IMUs require unique SDKs to operate/communicate. More generally, every IMU has some type of interface that allows users to send commands to the sensors, prompting specific actions from the sensors (i.e. start streaming data, stop recording data, etc.) Given our experience as a collective with coding projects and the small span of time between now and our final deliverable, an IMU with ample, easily available documentation will best suffice our project needs, hence the high weight for this category.

Streaming Rate. According to our research, we want an IMU streaming rate that matches our sampling rate of 100 Hz so that we don't have excess data but can still collect the 100 Hz of data. The Xsens DOT has a streaming rate of 60 Hz, which does not meet the sampling rate match criteria, but due to the internal processing algorithm to condense the data prior to streaming, we do not expect that to be an issue as our device will only give *semi*-real time feedback. Streaming rate was weighted higher because it is important to ensure minimal delay in data processing, but we are focusing on giving *semi*-real time feedback.

Lead Time. For our project, we only have a few weeks left to begin prototyping, so we are going to need our IMU to arrive within the week to meet our timetable plans for this project. This was given a lower weight because we did not want to sacrifice the technical performance due to our time constraints.

Additional Equipment. Additional equipment for our IMUs, if necessary, is fine, but for the simplicity of our project and our design, the less additional equipment required, the better, so this was given a low weight.

Straps/Adhesives Available. Straps/Adhesives being available for the IMU is preferred as it will make the process of prototyping/building our design much easier, but if this is more of a tiebreaker (hence the low weight) as if one IMU meets all our requirements better than another but doesn't have straps or adhesives available, we'll be going with that one anyways.

We used Xsens DOT as our baseline and gave all categories 0 ratings because of aspects such as lead time and compatibility with the processor. The highest weighted categories (4 rating) were simultaneous connections, gyroscope range, acceleration range, and documentation/library since these are critical to a successful device that can track gait and also critical to our team getting a functioning device within our time constraints. The Xsens DOT and the MMRL tied with the final score. The Xsens DOT distinguished itself in an integrated battery life indicator and documentation/libraries with various readily accessible documentations. The developer documentation for the Xsens DOT would allow us to focus on customizing our device whereas the MMRL restricted us to using their app for certain aspects of our design. Both IMUs were feasible for our design, but the Xsens DOT was more user friendly for our application. As a result, we purchased Xsens DOT IMUs for our final design.

Tactor Selection

For the decision to purchase tactors, we generated a specifications chart shown in Figure 20. Since our design involves around 30 tactors, we were concerned with the size and weight of tactors initially, but they proved to be smaller than anticipated so we expect the size and weight to be a non-issue. The power consumption of tactors was not available, so we supplemented with engineering analysis to ensure that would also not be a concern. We used the power supply and current draw specifications in our engineering analysis.

Category	Coin vibe motor	VPM vibrating disc motor	FeelVibe v2.0 (DRV2605L)
Tactor Type	ERM	ERM	ERM
Size [mm] (mm^3)	10 dia. x 2.7 (210)	12 or 10 dia. x 3.4 or 2 (385 or 160)	19 x 19 x 7 (2525)
Weight (g)	0.9	1.23	13
Power Consumption (W)	--	--	--
Power Supply (battery or external) (V)	3	3	2 - 5.2
Current Draw	--	80 mA (@3V)	--
Speed (RPM or Hz)	9000 RPM	12000 RPM	--
Used in Reserach?	N/A	N/A	Gonzalez-Rodriguez et al, 2019
Bonus Features	Comes with adhesive	Comes with adhesive	--
Price (USD)	$5.00	$3.50	$29.57

Figure 20: Tactor specifications chart

After discussing with our stakeholders, we decided that it was beneficial to purchase different tactors, and conduct empirical tests before selecting a tactor for our final design. We took this action because of two reasons: low cost of tactors and lack of time remaining for the project. We purchased 10 coin vibe motors and 10 VPM vibrating disc motors for testing due to their low cost, small size, and low weight.

Processor Selection

For the decision to purchase a processor, we once again utilized a decision matrix shown in Figure 21 with categories from our specifications. The processors we considered were the Arduino Uno Wifi R2, the Raspberry Pi 4, the Arduino MEGA 2560 R3, and the Arduino Nano BLE Sense.

Weight	Category	Range	Arduino Uno Wifi R2		Raspberry Pi 4		Arduino MEGA 2560 R3		Arduino Nano 33 BLE Sense	
3	Software GPIO pins	≥ 29	0	5	2	26	1	15	1	14
4	On-board memory (EEPROM)	More is Better	0	256 Bytes	2	up to 32 GB (on microSD card)	1	4 kB	-1	0
4	Memory during execution (RAM equivalent)	More is Better	0	6144 Bytes	2	2, 4, 8 GB	0	8 kB	1	256 kB
2	On board BLE/Wi-Fi capabilities	Yes	0	Yes	0	Yes	-2	No	0	Yes
3	Bluetooth simultaneous connections	≥ 5	0	5 for BLE	0	5 for BLE	0	5 for BLE	0	5 for BLE
2	Additional equipment	Less is better	0	Power supply; pin extension board	0	pin extension board; power supply	-1	pin extension board; power supply; Bluetooth module	-1	Pin extension board, power supply; header pins
2	Cost	Lower is better	0	$44.80	-2	$119 (microSD card with NOOBS)	0	$40.30	1	$31.10
		Totals	0		18		1		3	

Figure 21: Design matrix for processor selection

We determined each category in the decision matrix by referring to our requirements and specifications and our understanding of our project sub-functions. We assigned different weights to each category according to its importance. The weights range from 1 to 4, where 4 indicates the most important category. Each category is rated from -2 to 2, where 2 is the highest rating. The ratings are given relative to the Arduino Uno Wifi R2. The justifications for selecting each category and specification are listed below:

Software GPIO Pins. In order to activate each tactor individually, each tactor must have its own general purpose input/output (GPIO) pin controlled through software. Our concept has a 5x5 array of tactors on the stomach with individual tactors on the head, wrist, and both calves for a total of 29. The Raspberry Pi 4 has 40 general purpose input/output (GPIO) pins with 26 of them available as GPIO pins. The pins on a board can consist of ground, power supply, communication port, or GPIO, but we are only concerned with the number of GPIO pins. The Arduino Uno Wifi R2 has 14 total pins with only 5 of them GPIO pins. The Arduino MEGA 2560 R3 has 54 pins with only 15 GPIO pins. Both Arduino boards would need additional GPIO pins or an alternate way to activate tactors. The Raspberry Pi 4 is 3 GPIO pins short, so, given the time and expertise restraints, we may adjust our work for this semester to a design that has 26 or less GPIO pins to not introduce additional complexity using a pin expansion board. This category was given a high weight because sufficient pins are required for the activation of tactors on the array and the individual points.

On-board Memory. On-board memory will be used to store researcher set trial settings, IMU data, and a tactor activation record (start and stop times for each tactor). If the on-board memory is small, the sessions will have to be stopped more frequently to transfer the data from the processor to the researcher laptop for long-term storage. We considered on-board memory to be one of the most important categories because we wanted to safely store kinematic data and to avoid running out of storage space during a session.

Memory during Execution. Memory during execution is used for storage of data and variables when the program is executed. Our program will be machine learning, so we anticipate that we will need a large amount of memory during execution. Memory was given a high weight because it was important that the processor was capable of executing the algorithm without running out of memory.

On-board BLE/Wi-Fi Capabilities. On-board Bluetooth low energy (BLE)/Wi-Fi capabilities are a plus. If there are no on-board capabilities, we can add a Bluetooth module, but that is an additional cost and increased difficulty in all of the components communicating. This was given a relatively low weight because while on-board BLE/Wi-Fi capabilities are convenient and reduce complexity, there was an option to utilize separate Bluetooth or Wi-Fi modules.

Bluetooth simultaneous connections. For Bluetooth, there is a limit to the number of devices that can be connected and streaming concurrently. Bluetooth 5.0 can connect 7 devices simultaneously, but it is recommended to only connect up to 5 devices simultaneously for increased performance. BLE has a data throughput of approximately 0.27 Mbps. We used Equation 1 below as an approximation of the amount of data that needs to be streamed depending on the resolution (bits) and sampling rate of a selected IMU.

$$transmitted\ data\ =\ 5 * Resolution * axes * F_s \tag{1}$$

where the bits represents the number of bits in each sample, axes is the number of axes being sampled from, and F_s is the sampling frequency. For the selected Xsens DOT, the data is 32 bit and the IMU consists of 9-axis measurements in the accelerometer, gyroscope, and magnetometer. The streaming rate is 60 Hz. The transmitted data from the Xsens DOT is approximately 0.086 Mbps over BLE. This gives a safety factor of approximately 3, which is sufficient in the event that there is extra data sent to the processor. This gives us confidence that we will be able to transmit all of the Xsens DOT data from 5 devices using BLE. This was given a high weight because it was imperative that the processor was able to connect to and communicate with all five IMUs that we planned to use without loss of data.

Additional equipment. Some of the additional equipment we are considering are pin extension boards, a rechargeable power supply (to power the processor), a Bluetooth module, and a microSD card. All of the processors require some additional equipment, but it will vary based on the selected processor. This was given a low weight because of their relatively low cost.

Cost. For cost, the cheaper the processor (and the additional equipment), the better. Cost was not a deciding factor, though, because we wanted to be confident in the equipment to satisfy our selected design and specifications and requirements, hence it received a low weight.

After referring to this decision matrix, we purchased the Raspberry Pi 4 processor because it distinguished itself in important categories such as number of pins, on-board memory, and RAM capacity from other processors. An additional benefit with the Raspberry Pi 4 was a friendly UI that looks like a computer desktop, whereas the Arduinos did not have any UI. This was not a direct factor in our decision, but a benefit of the Raspberry Pi.

Design Driver #2

The second design driver addressed how data from the IMU could be transferred to the processor via Bluetooth in a timely manner without loss of data. To answer this driver, we first performed a product assessment of the potential IMUs and processors. For the IMU, it was important to know whether it could stream over Bluetooth, what the streaming rate would be, and what computer software would be capable of receiving/interpreting the data. For the processor, it was important to determine how many simultaneous Bluetooth connections it could sustain and if it was compatible with the software required to receive IMU data. This product assessment was performed because, before purchase, we could ensure compatible communication methods between the two components and determine which combination of components would best transfer data in a timely manner without loss of data. Figure 19 and Figure 20 display the different components we evaluated for IMUs and processors and describe in more detail our decision making process. Ultimately, we chose the Xsens DOT Motion Sensor as our IMU, which can sample data at 800 Hz, stream all of this data over Bluetooth at 60 Hz, and be received via an Xsens DOT server. A Raspberry Pi 4 was chosen as our processor, which can sustain 5 simultaneous Bluetooth connections and run the Xsens DOT server to receive the data and process it in Python.

In addition to product assessment, we also performed empirical testing using an IMU/processor prototype. In this experiment, we wanted to examine how much time it takes for IMU data to transfer to the Raspberry Pi 4 and study how much data is lost in the process. Our plan was as follows:

1. Connect 1 IMU to processor and perform simple movements for the IMU to collect (motion in one direction, motion in one axis)
2. Collect IMU data via processor and measure time of transmission. By using a simple motion to test the IMU, we can determine if the data collected by the processor meets expectations (no loss of data, etc.)

3. Repeat process, adding 1 IMU each time until all 5 IMUs are connected to the processor

By connecting a single IMU at a time, it allows us to closely examine the timing and data loss of each individual IMU in case there are any differences across components. Additionally, we can understand how adding more Bluetooth connections can impact data transfer and update the Xsens DOT GUI, our Python code, and/or our design set-up to make up for any loss of data or increase in transmission time beyond 2 seconds (see Requirements and Specifications). As a result of this procedure, we would expect our design to be able to communicate data from 5 Xsens DOT IMUs to our Raspberry Pi 4 within 2 seconds of movement, which will be a result of appropriate Xsens DOT GUI set-up and Python code. The results of this experiment are detailed in the Verification section.

Design Driver #3

The third design driver addressed the communication between the researcher UI and the Raspberry Pi. The researcher UI will enable the researcher to select the IMUs they want to take data from, select the feedback scheme to use for a given trial, and select the post-processing algorithms to use for a given trial. The Raspberry Pi will need to process those settings for correct device functionality. The Raspberry Pi will also need to save the trial data (IMU data, tactor activation record, date, time, etc.) and transfer the data from the Raspberry Pi to an alternate storage location (i.e. USB, cloud, etc.). To answer this design question, we did a product assessment of processors and IMUs (Design driver #1) and empirical testing. Previously developed circuit schematics were also used.

In the product assessment of processors, we looked at on-board storage capacity, processor UI, and availability of developer documentation for each processor. For the IMU product assessment, we looked at the data communication methods and availability of developer documentation. Based on the product assessment, we determined IMUs and a processor that would be able to communicate with each other and with a researcher UI on a laptop/monitor. We also determined a processor that would be able to save and store all trial data. Not included in the product assessment was the ability for us to get the components communicating and functioning properly. The product assessment assumed that we would be able to configure all components to fully functioning state. Additional analysis was done to ensure that all components could be configured together.

To date, subsystem prototyping has been completed to test the Raspberry Pi and Xsens DOT Bluetooth communication to start/stop data collection and to test storing IMU data on the Raspberry Pi. Xsens has open source software for an Xsens DOT server on a Raspberry Pi [47]. We configured the Xsens DOT server on the Raspberry Pi and connected all 5 IMUs to the Raspberry Pi over Bluetooth. From the Xsens DOT GUI, data collection was started and stopped and the data was saved onto the Raspberry Pi. Figure 22 shows the Xsens DOT GUI displayed in a browser on the Raspberry Pi.

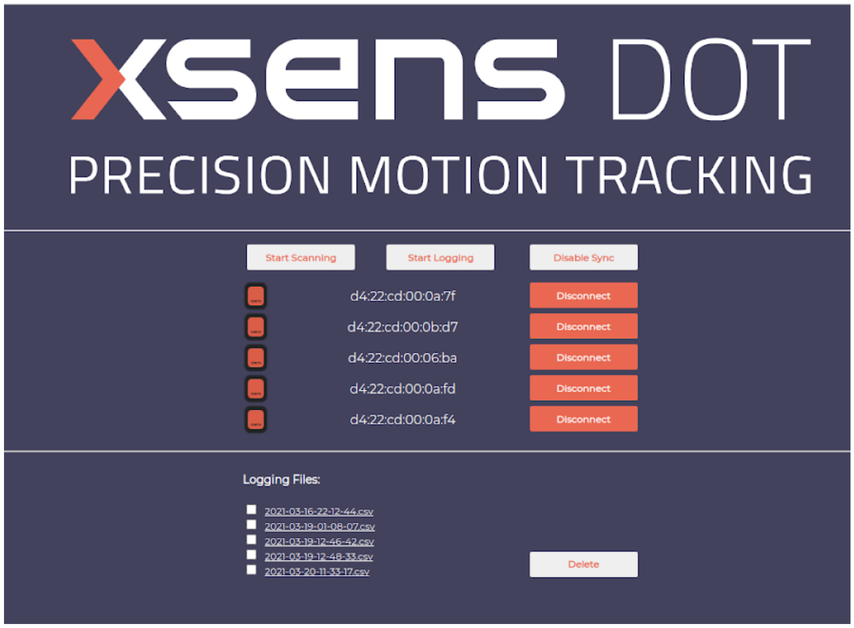


Figure 22: Xsens DOT GUI on Raspberry Pi.

Additional empirical analysis needs to be completed to fully show a researcher UI proof of concept for changing trial settings. In the final researcher UI, we will include an extension to the Xsens DOT GUI for the researcher to be able to select the tactors and the post-processing algorithm used for a specific trial. To demonstrate a proof of concept, we will use empirical analysis to show that we can add a researcher input section that will automatically get processed in the scripts being executed on the Raspberry Pi. The proof of concept researcher UI will have at least three inputs (a text box, a drop down menu, and various buttons) to demonstrate that our design can be adapted to process many types of researcher input. The various inputs will also allow us to gather stakeholder feedback and determine the best way to collect the researcher settings. Based on the results of the completed and planned empirical analysis, we are confident that our design will be able to be reconfigured for tracking motion of different body segments and providing various feedback schemes depending on the desired trial. The final UI is presented in detail in the "Detailed Design Solution" section and future analysis is done in the form of verification and presented in the "Verification" section.

Design Driver #4

The fourth design driver addressed the tactor activation aspect of our design. We wanted to determine how we could use the Raspberry Pi to activate the tactors in the 5x5 array on the torso as well as the tactors located on other body segments. To answer this design question, we used online documentation, theoretical analysis involving circuit schematics, and empirical tests.

Due to the limited in-person time and the delay in purchasing components, the online documentation and circuit schematics were used to prepare us for the empirical testing and ensure that we would be properly wiring the tactors without damage to our components. Online documentation and circuit schematics limited the time we needed to be in-person together, informed what components were needed for the circuit, and informed the tactor activation scripts. Circuit schematics allowed us to quickly and easily try different wiring configurations using an Arduino Uno R3 and a Raspberry Pi 4 and varying electrical components including transistors, h-bridges, and transistor arrays. They provided a minimum viable prototype that would allow for easy experimentation with adding and activating tactors using a processor without purchasing any components. We used the circuit schematics to inform our component purchasing and our physical tactor wiring. Figure 23 shows the circuit schematic used to activate two tactors with the Raspberry Pi and two transistors. Black wires are used to indicate ground, red wires are used to indicate connection to a 3.3 V supply pin, and blue wires indicate tactor connections that can turn the tactors on and off.

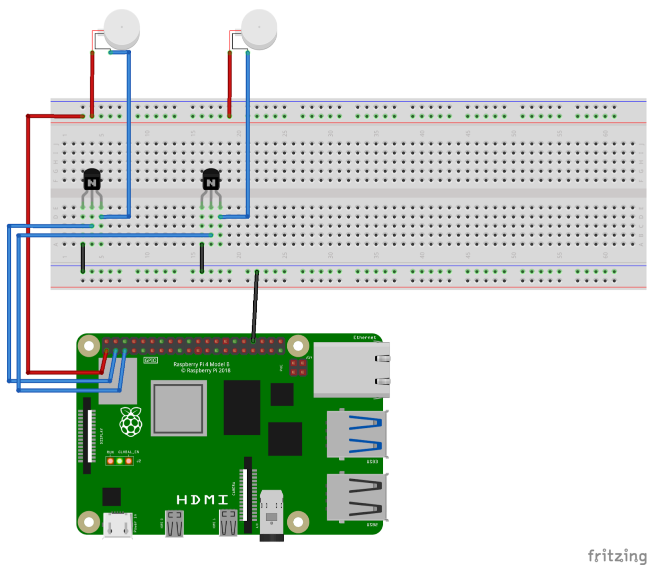


Figure 23: Circuit schematic showing wiring to activate two tactors individually with a Raspberry Pi.

We were able to use online software to simulate tactor activation using the same wiring but with an Arduino Uno R3 to give us confidence that the wiring was correct, but we recognize that the online simulation assumes ideal electrical components, so the best way to confirm our results was with empirical testing. Using the circuit schematic to wire our physical circuit, we performed empirical testing to activate the tactors. The tactors are able to be activated either simultaneously or individually for any desired length of time. The scripts to activate the tactors are included in Appendix B.1. We are confident that we will be able to adapt the tactor activation scripts to activate the tactors based on IMU data conditions (design driver #5) and also be able to scale up the code to activate additional tactors. The code and the circuit is repetitive for each additional tactor, so to show a proof of concept, we only used two tactors in our analysis.

In doing the empirical testing, we realized that using single transistors to activate each tactor required a lot of wires, which is not ideal for a wearable device. To reduce the number of wires, we are looking into replacing transistors (can activate 1 tactor) with either an h-bridge (can activate 4 tactors) or a transistor array (can activate 8). Additional empirical analysis would need to be completed using the new components to give us confidence that alternative components will work for our design. The additional empirical analysis will allow us to select the electrical components we will use in the final design to minimize wires without sacrificing design functionality. Empirical analysis is best since h-bridges and transistor arrays are very cheap (<$1), but theoretical circuit schematics were also developed for each case (activating 4 tactors using an h-bridge (Figure 24); activating 8 tactors using a transistor array (Figure 25)). Black wires are used to indicate ground, red wires are used to indicate connection to a 3.3 V supply pin, and other wires appear in pairs to indicate tactor connections that can turn on and turn off each individual tactor.

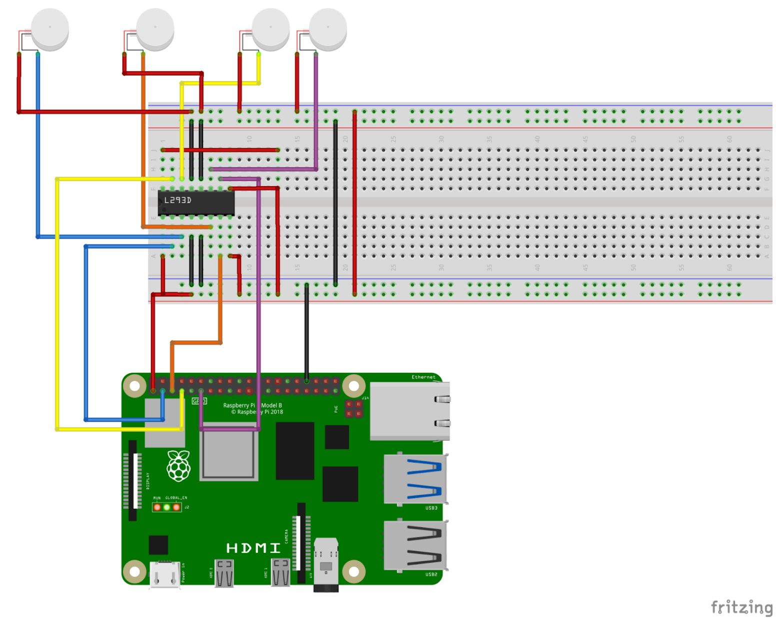


Figure 24: Circuit schematic showing wiring to activate four tactors individually with a Raspberry Pi and an h-bridge (L293D).

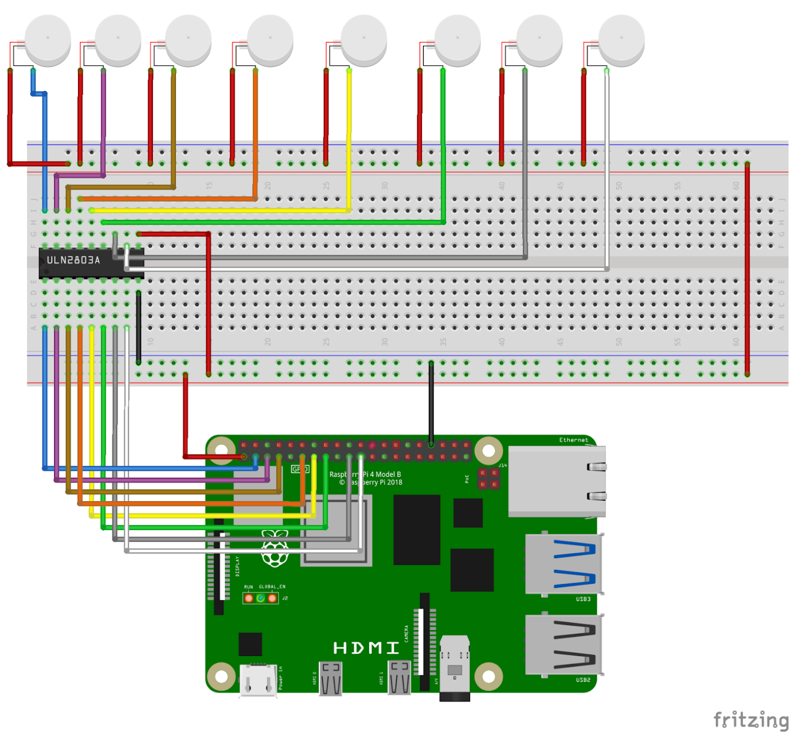


Figure 25: Circuit schematic showing wiring to activate eight tactors individually with a Raspberry Pi and a transistor array (UNL2803A).

As a result of the analysis, we are confident that the Raspberry Pi can be used with a Python script to activate tactors either individually or simultaneously. Since we performed empirical analysis on two different types of tactors, a coin vibe motor and a VPM vibrating disc, we were able to use our empirical analysis to decide which tactor we would like to pursue for our final design. We selected the VPM vibrating disc due to the larger contact area and the durability of the tactor wires relative to the coin vibe motor.

Design Driver #5

The fifth design driver addressed configuring the Raspberry Pi to be able to receive streamed data from the Xsens DOT IMUs and activate specific tactors based on the IMU data. A product assessment for processors and IMUs was done to show that our design was feasible with the components we purchased. The product assessment gave us some confidence that our design would work, but the product assessment assumed that we would be able to get all of the components configured in less than one month. To show a minimum viable device that can activate tactors based on IMU data, empirical analysis was performed. Due to our time constraints with the IMUs arriving less than a week ago, we recorded data on an IMU and transferred the data over Bluetooth to the Raspberry Pi after the trial. Additional engineering analysis needed to be performed to show that the Xsens DOT IMUs can stream data over Bluetooth to the Raspberry Pi (Design driver #2), and is discussed in the “Verification” section.

In the empirical test, the Xsens DOT GUI was used to connect one IMU to collect data. Additional empirical testing is planned to connect two IMUs simultaneously to collect and process data. Data was recorded as we slid one IMU across a table. The IMU data collection was started and stopped via the Xsens DOT GUI (over Bluetooth). Data was collected on Euler angles (show IMU orientation relative to local reference frame) and free acceleration (acceleration minus gravity relative to local reference frame) in the x-, y-, and z-directions as shown in Figure 26 and Figure 27. The local reference frame of the Xsens DOT is shown in Figure 28. This analysis shows that we are able to receive IMU data on the Raspberry Pi.

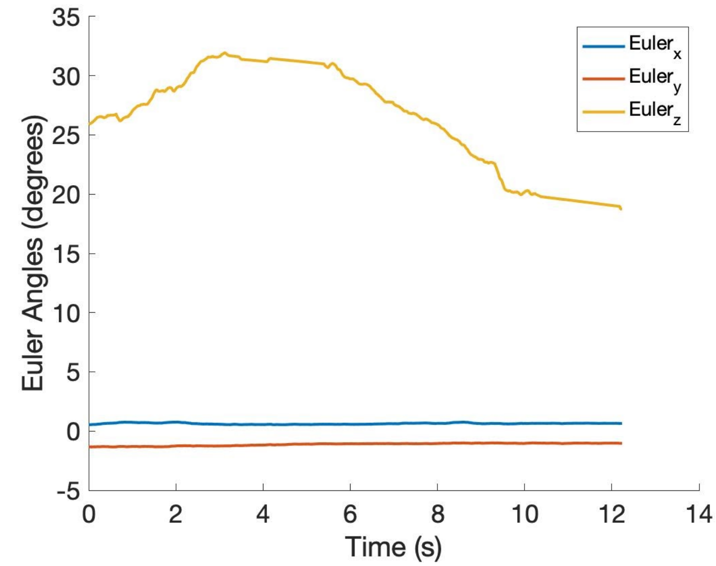


Figure 26: Euler angle data from one Xsens DOT as it was slid across a table.

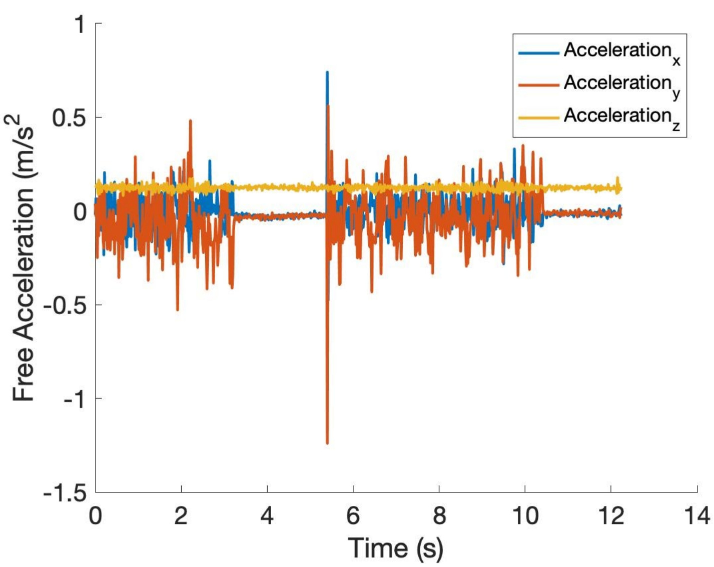


Figure 27: Free acceleration data from one Xsens DOT as it was slid across a table.

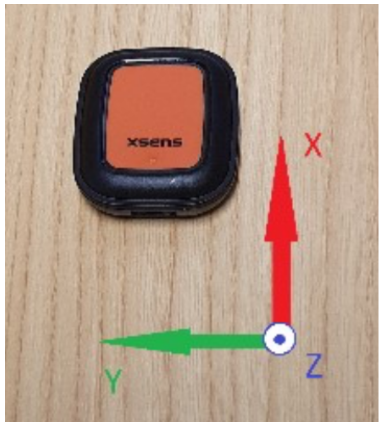


Figure 28: Xsens DOT local reference frame.

We implemented a Python script that is executed on the Raspberry Pi (script included in Appendix B.2). The Python script simulates data being sampled in real time. As a basic test to combine IMU data and tactor activation, we set arbitrary IMU parameter thresholds for Euler_x (threshold 0.57) and Euler_z (threshold 27). One tactor was associated with Euler_x and a second tactor was associated with Euler_z. If the recorded IMU parameter was above the arbitrary threshold, the tactor associated with that parameter was turned on. When the recorded IMU parameter was below the threshold, the tactor associated with that parameter was turned off. The tactors were wired according to the circuit schematic in Figure 23. Based on this analysis, our design can have variable tactor activation based on IMU data. Additional analysis was performed and detailed in the "Verification" section to ensure synchronization of data from multiple IMUs is achievable.

We are confident that the script can be scaled up to include additional data processing and tactor activation. Since Python is an interpreted language (as opposed to a compiled language like C++) and as the data is streamed and post-processing and tactor activation become more complex, the speed of program execution could introduce a delay in data processing and, therefore, in giving feedback to the wearer. This is a potential oversight in our selection of Python as our coding language, but due to team member experience with Python and C++, we don't anticipate huge difficulty if we must refactor our scripts. We did some pre-planning if this were to happen, as we have a tactor script in Python and C++ (Appendix B.3 for C++ tactor activation). We would need to install C++ libraries and configure the Raspberry Pi to compile and execute the C++ script.

Design Drivers #6 & #7

The final design drivers addressed the power concerns of the full tactor subsystem used in our device. The full tactor subsystem can be broken down into two segments: one is the 5x5 tactor array located at the trunk and the other is a series of individual tactors located at specific body parts. The question generated from this design driver is as follows: what power supply design will allow for the support of all tactors within the subsystem being triggered? To address this question, we utilized simple electrical engineering knowledge on power absorption and dissipation for a theoretical circuit of 30 tactors in parallel, a worst-case scenario given the current requirements for each tactor. Using Equation 2 below, we were able to calculate the total power absorption from all tactors.

$$P_T = (V_{OP})(I_{OP})N \quad (2)$$

where P_T is the total power required to operate all tactors at once, V_{OP} is the operating voltage of a single tactor, I_{OP} is the operating current of a single tactor, and N is the number of tactors within the full subsystem. With this value in hand, a safety factor of 1.5 was applied (Equation 3) to ensure that whatever power supply is utilized, it will provide energy to power all components of the full tactor subsystem without interruption/failure.

$$P_{T,f} = (V_{OP})(I_{OP})Nf \quad (3)$$

where $P_{T,f}$ is the total power required to operate all tactors at once with a safety factor applied, and f is the applied safety factor. In Equation 3 above, specifications for the VPM2 tactors were used [48]. This tactor has an operating voltage of 3 V, and operating current of 80 mA. By utilizing 30 of these tactors with a safety factor $f = 1.5$, we found that the total power required to operate all tactors at once will be 10.8 W. From the first interview with our stakeholders, we have outlined that the full tactor subsystem should operate for ≥ 2 hours, the duration of a standard trial with an IWVD. Thus, any utilized power supply for the full tactor subsystem must provide ≥ 21.6 Wh (Watt-hours) of power. We will use this analysis to inform our decision of which power supply to purchase for the tactors. If we are able to find a power supply that satisfies our power requirements, we are confident that our design will be able to successfully activate all tactors simultaneously. The tactors would only vibrate simultaneously as a test and never when on a person's body.

Engineering Analysis Conclusion

Though at this point we did not finish all 18 engineering analysis procedures, the 13 procedures that we did complete gave us confidence to pursue our design. From Product Assessment, we found that the Xsens DOT IMUs, VPM2 vibrating disk motor/Coin vibe motor tactors, and the Raspberry Pi 4 processor were commercially available at a reasonable price and would fulfill the needs of our design. This includes the ability to process kinematic data from 5 sources that contribute to tactor activation (Design Driver #1), timely Bluetooth communication between IMUs and the processor (Design Driver #2), and the ability to configure the processor to store, send, and receive information to our user interface (Design Driver #3). Additionally, the components and software we chose were user friendly enough for our team to assemble the design within the one month we had left before our final design communication. Our subsystem prototype of the researcher UI configuration with the Xsens DOT IMUs physically proved that it was possible, using our chosen components, to track motion and send this information to our user interface, where it gets saved locally on the processor. Our circuit schematics theoretically suggested that we could control which tactors we activate, and our physical prototype with tactors and the Raspberry Pi proved this to be true. Finally, our power consumption calculations based on online component documentation gave us theoretical values for what power supply/supplies we would need for our design. After conducting a quick search for available power supplies, we know there are commercially available and reasonably priced power supplies that could fulfill the power needs we calculated for our design.

All of the engineering analysis procedures we completed pointed us towards easily attainable components that would make our design feasible. The components we found seemed to fulfill each of our Design Drivers. This, combined with the fact that none of our procedures raised red flags for the feasibility and quality of our design, suggested that pursuing our current concept would be successful. The remaining five engineering analysis procedures were completed during our verification process and are detailed later in this report.

Risk Analysis

We also performed a risk analysis for our device to address hazardous situations and address how we plan to minimize the risk in our design; specifically, we used the standard risk assessment chart to identify potential safety hazards and risks with our design both for the wearer and for device malfunction. The full analysis can be seen in Figure 29 and Figure 30. The analysis includes potential hazards, situations that involve that hazard, the likelihood of the situation occurring, the impact on the wearer, the rating (1-4 with 4 being high), implications for technical performance, and actions we plan to take to minimize the hazard. We performed a risk analysis because it allowed us to view our design holistically to analyze the different risks and safety concerns for the wearer and the device.

Risk to the Wearer

Hazard	Hazardous Situation	Liklihood of Occuring	Impact	Rating	Technical Performance	Action to Minimize Hazard
Trip	Wires connecting a processor and tactors located at the calves, wrist, and head could become loose and have excess slack causing the wearer to trip and fall	Medium	Serious	4	Significant reduction in technical performance if wires are disconnected	Ensure all wires are the proper length and secured to the body to handle slack during giat
Tangle	Various straps and excess material could become lose and distrupt the wearer's gait and potentially cause them to fall	Medium	Serious	4	Significant reduction in technical performance if the wearer's gait data is affected by loose material	Trim all excess material as much as possible as well as tape it to the design/to the wearer whenever applicable
Overheat	The power supply, located on the wearer's back, has been in use the entire session and gets too hot	Medium	Serious	4	Minimal reduction in technical performance if the equipment does not shut off	Put the power supply on the outside of the wearer's clothes and/or have an additional buffer material to reduce the heat that goes to the wearer
Balance	IMUs, tactors, a processor, and power supply are all attached to the wearer. The mass of all components together can cause the wearer to become unsteady and fall	Low	Serious	3	Significant reduction if wires are disconnected or parts cannot survive a fall	Ensure that weight is symmetrically distributed and is light enough (according to literature) to not cause balance issues
Blood restrictions	Straps are used to connect IMUs to the feet, wrist, and head and tactors to the trunk. They are pulled tight to minizmize the liklihood of slipping during trials but are pulled too tight and cause some blood cirulation issues	Medium	Serious	3	No reduction in technical performance	Utilize elastic straps as well as provide information to our sponsors on how tight the straps should be pulled
Strong vibrations	Vibration strength of the tactors are too high and can become disorienting to the wearer resulting in risk of dizziness	Low	Moderate	2	No reduction in technical performance	Test the vibrotactors with ourselves and ensure that the vibrations are as minimally disorienting as possible
Shock	Wires from power supply, tactors, or processor become exposed and come into contact with the wearer posing a shock risk	Medium	Moderate	2	No reduction in technical performance	Ensure the proper attachment of wires as well as provide non-conductive casings for each and every wire
Scratch	Sharp wires and/or corners of our straps could scratch the wearer	Low	Moderate	2	No reduction in technical performance	Ensure that all wires are securely attached and that all sharp edges of the device are filed down or covered with something soft

Figure 29: The risk assessment chart for our device based on risk to the wearer.

The highest rated risk we identified involved tripping. This directly relates to our “wearable” requirement as we want to ensure that there is no excess slack in the wires that could cause the wearer to trip and fall, but also ensure that there is enough slack so that their motion is not impeded. To minimize this hazard, we plan to ensure proper wire lengths (lower back to leg) but still ensure that the device is wearable for many different people. Any slack in wires due to different body sizes will be managed by securing wires to the body with tape.

The next risk identified involved tangling. This also applies to our “wearable” requirement as we want to ensure that no excess or loose material can become entangled with the wearer’s arms or legs as they go through their natural gait cycle. This could both cause a safety hazard to the wearer by potentially causing them to lose their balance as well as cause severe harm to the data if the tangling with excess material impacts their gait and causes vibrotactors to go off when they shouldn't. To minimize this hazard, we plan to cut off all excess material (whenever possible as the "customizable" aspect of our design makes certain that there will be some excess for smaller wearers) as well as use tape to connect any loose material so that it won't have the opportunity to dangle and become entangled with the wearer.

The third risk that we identified involved overheating. Whenever dealing with any electrical components, such as our power supply which is in charge of powering 30+ tactors, the risk of them overheating and potentially causing harm to/burning the wearer is a possibility. To minimize this risk, we plan to place the power supply on the outside of our elastic straps and outside of the wearers clothing. This will help prevent direct contact between the wearer and the power supply in the possibility that our power supply will reach an uncomfortable level of warmth.

The next risk that we identified involved balance issues. As our device is an additional amount of weight as well as a slightly unnatural addition to the wearer's body, there could be a slight additional fall risk associated with our device. To minimize this risk, we plan to ensure that our device has evenly distributed weight as well as being light enough that we believe, due to our research, will make the additional risk of balance issues minimal.

Another risk that we identified involved potential blood flow restriction. As we are placing straps and components around the wearer's body, if these straps are too tight, they could restrict flood flow both to their appendages as well as in their stomach. This could cause severe uncomfortability as well as potential issues such as fainting and loss of feeling in rare cases. To minimize this risk, we plan on using elastic straps that more easily conform to the wearer's body as well as provide information to the researcher on exactly how the straps should be put on/how tight the straps can be in a safe way.

The next risk that we identified is involved strong vibrations. As we are using vibrotactors, the vibrations on or near a person's skin could distract them and cause dizziness or other bodily confusion. This could make falling or tripping more likely. To minimize the risk, we plan on testing the vibrotactors repeatedly to make sure that they can be felt but not so firmly that it causes overstimulation.

Another risk that we identified involves shock from the electrical components to our device. As we are using electrical circuits and parts, if any electrical component or wire touches the skin of the wearer, it could shock them in a painful way. To minimize this risk, we plan on casing the electrical components of our device in non-conductive material as well as repeatedly checking to make sure that everything is attached safely.

The final risk that we identified involves potential scratching of the wearers skin. As our device does involve firm and metal components, if the wearer's skin hits a tactor wrong or rubs against the extruding corner of a piece of velcro the wrong way, they could be painfully scratched. To minimize this risk, we plan on filing down/covering the sharp edges of our device to make sure that the contact points that could cause scratching are limited.

Risk of Device Malfunction

Hazard	Hazardous Situation	Liklihood of Occuring	Impact	Rating	Technical Performance	Action to Minimize Hazard
Water Damage	Potential sweat from the wearer could get onto the device and cause it to malfunction and break	Low	Serious	3	Significant reduction in technical performance if water damage breaks one/multiple components	Use waterproof/resistant casings of our devices and put the important components in low-sweat areas
Overheat	The power supply overheats from use and breaks	Medium	Serious	4	Significant reduction in technical performance if the power supply breaks	Limit the time and power required for our device to function as much as possible and stop use when it begins to get hot
Disconnected wires/tactors	Tactors could fall off/wires could become disconnected from our device due to constant motion and wear	Low	Moderate	2	Will have a signficant reduction in technical performance, will immediately require the session to be stopped and the wires to be fixed	Personally solidify connects with the wires and tactors and provide a signal to the researcher that will notify them if a tactor becomes disattached
Components failing	Components (such as IMUs, tactors, microprcessors, etc.) could suddenly break due to random circumstances (overuse, mechanical failure, etc.)	Low	Serious	3	Significant reduction in technical performance if one/multiple components become unfunctionable	Buying quality components and testing them under a variety of circumstances to ensure function
Corruption	The SD can occassionally corrupt if the Raspberry Pi is turned off while the SD card is stylle writing data. This can wipe the entire SD card, and requires the enitire Raspberry Pi operating system to be reinstalled	Low	Serious	4	Significant reuction in technical performance if data is lost / the Raspberry Pi must essentially be restarted	Regularly backing up the SD card to the computer or another location

Figure 30: The risk assessment chart for our device based on risk of device malfunction.

The first risk that we identified involved water damage to the device. As the wearer will be performing tasks of physical exertion, they may potentially perspire, and if their sweat gets into the mechanical components of the device, these components may break. To minimize the risk, we plan to cover our most vulnerable components in a protective casing as well as do our best to keep electrical components away from locations where the body is more likely to perspire (ex. Armpits, back of knees, etc.)

The next risk that we identified involved the device overheating. This risk is both a potential problem to the wearer and the device itself as overheated components may break/not work as well as they used to before. In rare cases, the components may also shut down, making our device not function at all. To minimize this risk, we plan to limit the components in use at one time (ex. Not using certain tactors if we don't need them) as well as make sure to stop trials/let the device rest if it begins to get hot.

The third risk that we identified involved different wires and tactors becoming disconnected in the middle of a session. Due to the motion of the device and wearer, wires and tactors might become disconnected and ruin the data received from trials without the researcher knowing. To minimize this risk, we plan to make sure that the researcher checks the wires throughout the sessions as well as potentially create a programmed signal that will alert the researcher if anything gets disconnected.

The next risk that we identified involved components of our device failing for other reasons. Whether it be for overuse, random mechanical failure, or something else, if components of the device such as the IMUs, tactors, and/or processor break, the device will likely no longer be able to function and fill its desired role in research. To minimize this risk, we plan on using only good, quality components as well as testing the components between some sessions to ensure consistency.

The final risk we identified involved the SD card of the device which can become corrupted if the Raspberry Pi is shut off too early/before the SD card is done writing data. This could be an incredible problem if it causes researchers to lose data from previous trials or have to pause and restart trials after having to redownload the entire Raspberry Pi operating system. To minimize the risk, we plan to backup the SD card often to an external location and advise the researchers to do the same.

Detailed Design Solution

The final design solution for a customizable wearable vibrotactile feedback display for gait biofeedback consists of a researcher interface and a wearable design. The researcher interface and the wearable sub-functions of our design come together for the researchers to run gait biofeedback trials. All of the wearable components are put on a wearer and the five IMUs can track various gait kinematics that get streamed over Bluetooth to the Raspberry Pi. The researchers can then use the UI settings and a data processing algorithm to provide the wearer vibrotactile feedback and observe any changes in gait due to the provided feedback.

Detailed Design Solution - Researcher Interface

The researcher interface was designed to allow researchers to have a customizable user interface to quickly reconfigure settings for gait biofeedback trials. Within the researcher interface, researchers can set trial settings, create new data processing settings, connect Xsens DOT IMUs, start/stop data collection, and test various tactor configurations. The user interface is built upon the Xsens DOT Server, which is a web server that can connect IMUs and start data logging with Xsens DOT IMUs on a Raspberry Pi. The web server is built using Node.js in combination with Noble. The web server is written in Javascript and HTML/CSS and the data processing script is written in Python. Data processing settings are saved in JSON format. The web server and the data processing program are both started simultaneously with shell scripts. All aspects of the researcher interface were designed and implemented by our team except for the "IMU Settings" section. A link to a video demo showing the full scale researcher interface can be found in Appendix C.

When a researcher wants to run a gait biofeedback trial, they will run the server and the data processing script with one line in the command line and then load the web server in a browser. The first section of the researcher interface, titled "Trial Settings," allows the researcher to enter the subject number, the exercise type, the trial number, the IMU locations, and the tactors that are in use as shown in Figure 31a. The IMU locations that are entered, are propagated to the rest of the settings for easier reference to which IMU is which. Depending on which tactors are selected as in use, additional settings will be displayed (Figure 31b). If the torso array is selected, the researcher will select the tactor pattern and the data processing settings. If the leg tactors and/or the side torso tactors are selected, the researcher will select the data processing settings for each set of tactors. In the current design, the data processing options are "Trunk Sway," "Heel Strike," or "Custom." "Trunk Sway" and "Heel Strike" can be selected and there are predetermined settings for the IMU placement, the IMU measurements of interest, and IMU measurement thresholds. If "Custom" is selected, additional settings are displayed (Figure 32) where the researcher can create a new data processing scheme that can be saved and loaded for future trials. To make a new data processing scheme, first, the researcher must select which IMU locations they are interested in collecting data from. For each IMU location that is selected, data measurement settings are displayed where the researcher selects which data measurement(s) are of interest and what the threshold is. In the current implementation, the threshold value is used to determine when to turn tactors on and off. A filename must be entered to save the data processing scheme and the "Save Custom Processing" button is pressed to save the settings in a consistent json format for future use. A new radio button will need to be manually added to the data processing section to be able to select the new scheme, but that process can be automated in future design iterations.

Once all trial settings have been entered, the researcher will click "Update Settings" to save the settings and move on to configuring data collection.

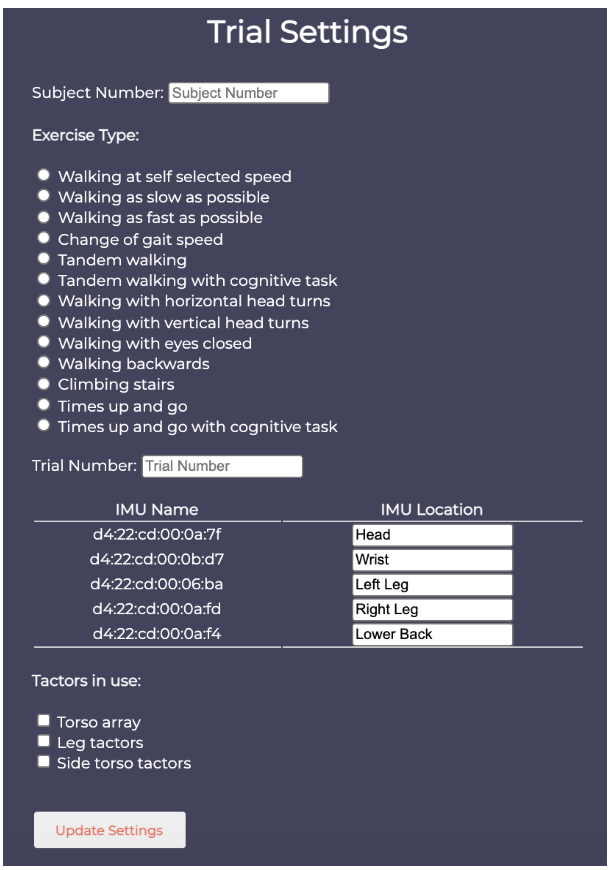


Figure 31a: The researcher interface where trial settings can be updated.

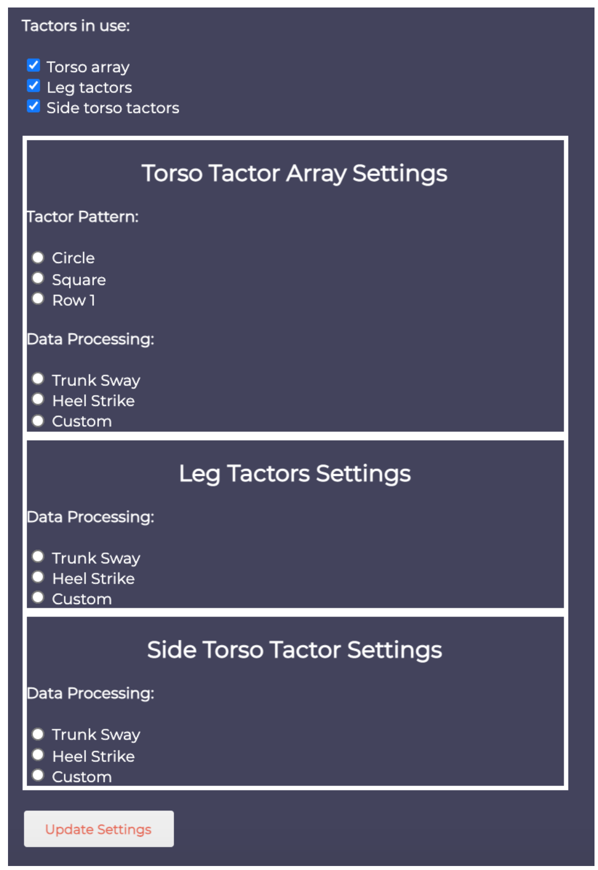


Figure 31b: Additional settings displayed depending on which tactors are in use.

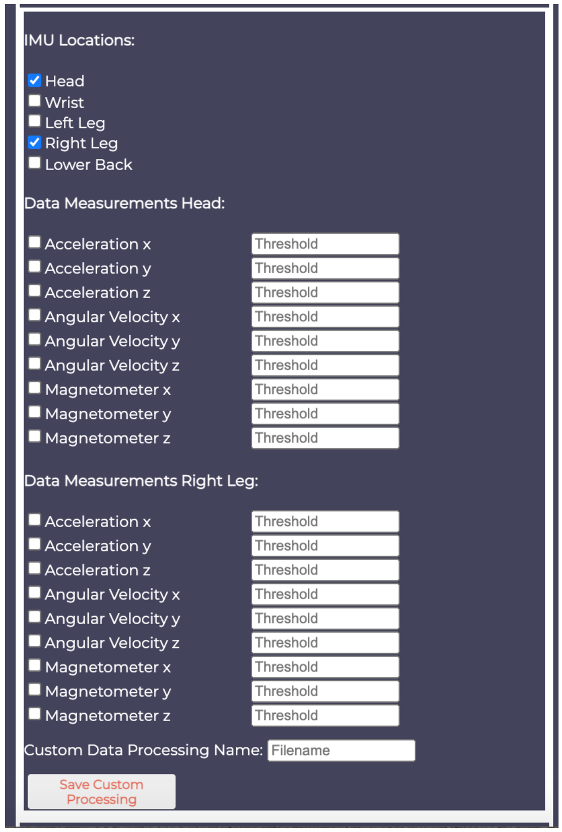


Figure 32: Custom data processing settings.

The next section of the researcher interface is titled "IMU Settings" (Figure 33). Here, the researchers will select which IMUs they would like to connect and take data from. They can also start and stop data collection and Bluetooth streaming in this section. There is a sub-section titled "Logging Files" (bottom section of Figure 33) where the trial data can be downloaded directly from the server. The raw IMU data is also stored locally on the Raspberry Pi with all of the trial settings in one csv file.

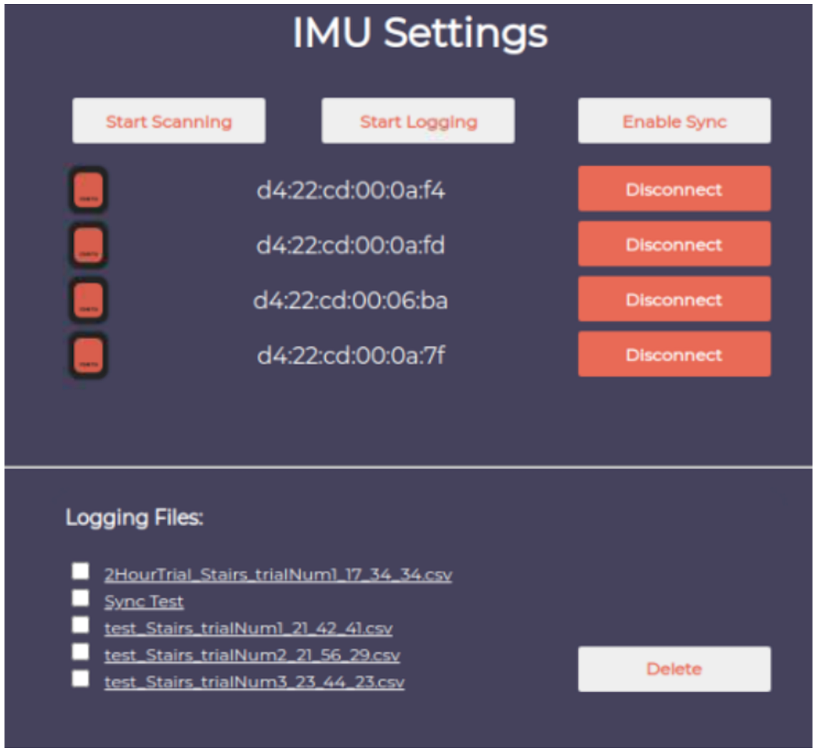


Figure 33: Four IMUs are connected and ready to begin data collection. The "Logging Files" section lists all of the files with saved trial data and trial settings.

The final section of the researcher interface is titled "Test Tactors" (Figure 34). The researcher can click one of the three buttons and the selected tactors will turn on for three seconds and then turn back off. This allows the researcher to test the tactor connection prior to putting the wearable device on the wearer. If the torso pattern array is selected, a tactor pattern must be selected in the "Torso Tactor Array Settings" section.

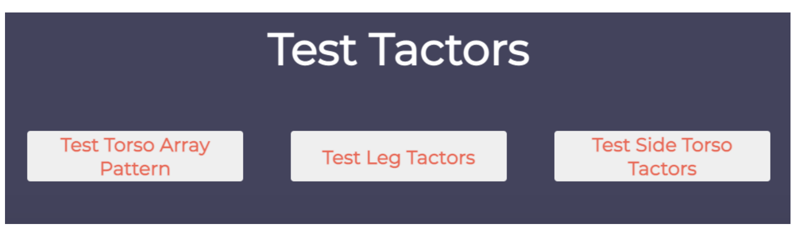


Figure 34: The "Test Tactors" section where the researcher can test tactor connections

With the current implementation, the IMU data is streamed (in real time) over Bluetooth into a csv file where a Python script processes the data. The same python script is used for data processing and tactor activation. For a proof of concept, the data is processed according to a logical OR statement, but the script was written in a way that allows the researchers to easily change the data processing algorithm. We abstracted the data processing into a separate function, so the researchers can update just one function with a new data processing and the entire device will function without additional changes. The current logical OR data processing turns the tactors on and off based on the predetermined thresholds provided in the data processing schemes. If the IMU reading is above that predetermined threshold, the tactors that are in use go on. Once the IMU reading drops below that predetermined threshold, the tactors in use go off. Our proof of concept has the tactors in use go on and off together but the code can be updated to have the tactors go on and off variably.

The researcher interface was designed for scalability and usability. This is the first iteration of the design, so the code was structured in a way that will allow the researchers to add, remove, and/or modify the settings and the settings options. The researcher interface is also configured so that the server is started at the beginning of a session and many trials can be completed before turning the server off at the end of a session. New trial settings can be entered throughout the session without having to restart the server. The trial settings will also carry over from one trial to another, so to run a trial with the exact same settings, the researcher will only need to increment the trial number. The entire researcher interface repository is stored in private repo on GitHub. Appendix D provides a link to the researcher interface documentation provided on the private GitHub. Suggestions to stakeholders for improvements in future design iterations and next steps to expand on the proof of concept we demonstrated can be found in the "Discussion and Recommendations" section.

Detailed Design Solution - Wearable

The wearable design solution was made to satisfy the requirements and specifications outlined in Table 3. As an overview, this design solution is made of six components: a wearable torso component, head component, wrist component, two ankle components, and a shin component. These components were designed to accommodate locations where gait data collection and/or biofeedback would be provided. Each component is described in detail below.

Torso Component Fabrication

The core of the torso component is an elastic strap with all other components mentioned in this subsection being secured to it by means of stitching. To secure the torso component, male and female straps of velcro have been secured to the torso strap, and can interface with one another through the assistance of a buckle component, attached to the end of the elastic strap. On the strap, there are 22 male-female tactor housing pairs. The female components of the pairs are secured into the strap and velcro strips during fabrication, and are arranged in a 4 x 5 array for customizable vibrotactile feedback. Ideally, the array should be 5 x 5, but due to I/O pin constraints from the utilized processor, the array bounds had to be restricted. To the left and right of the 4 x 5 female tactor housing array are two individual tactors for individual zone vibrotactile feedback. Male-female tactor housing pair CAD renderings and 3D-printed physical models are showcased below in Figure 35.

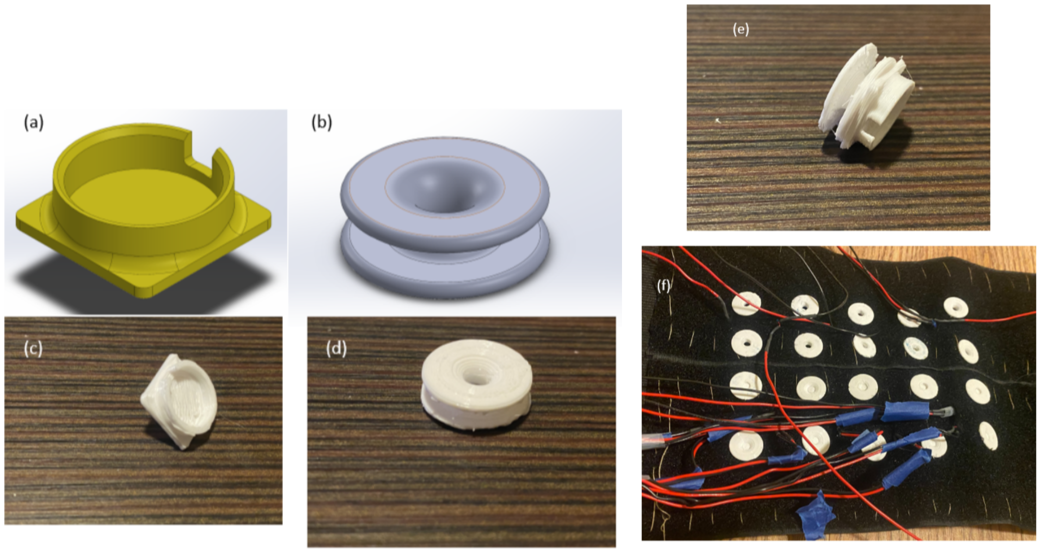


Figure 35: Male-female tactor housing pair CAD renderings and 3D-printed physical models of male-female tactor housing pairs. (a) and (c) display the CAD and 3D printed models of the female tactor housing. (b) and (d) display the CAD and 3D printed models of the male tactor housing. (e) shows the male-female tactor housing pair assembled, and (f) shows the tactor housing implemented into the torso strap in the form of a tactor array.

All tactors utilized in the torso strap are secured in the cavity in the male tactor housing component. The stem of the male tactor housing component is inserted into the female tactor housing component. This connection is semi-permanent to ensure that tactors can be attached/removed in the event of maintenance.

Wires leading from the tactors are fed into the tactor electronics box. The tactor electronics box is made up of 3D-printed components (a base and walls). CAD and physical prints of these models can be seen below in Figure 36.

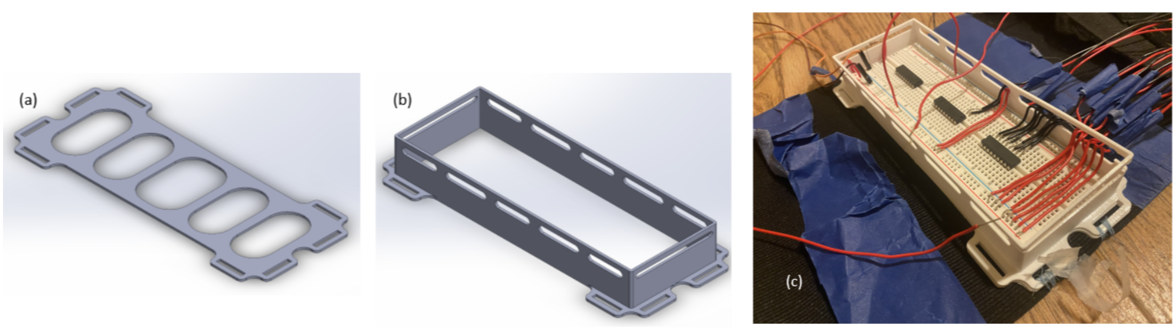


Figure 36: The CAD model and 3D printed tactor electronics box to help with wire management. (a) CAD of the base of the electronics box that forms the base underneath the breadboard. (b) CAD of the side walls of the electronics box, which contains small windows to thread wires through. (c) 3D printed electronics box with bread board inserted.

Within the tactor electronics box are a breadboard and electrical circuit components (transistor arrays, wires, a resistor, etc). Depending on what the processor deems as appropriate feedback to convey to the device wearer, the 4 x 5 tactor array and/or the two individual tactors resting at the sides of the 4 x 5 tactor array will actuate accordingly. This actuation is driven by GPIO pins, sending voltage signals to each tactor with precision. This precision is achieved through the use of the UNL2803A transistor array component. This array manages up to 8 GPIO signals and thus handles the actuation of 8 individual tactors within the wearable solution. Three of these units were utilized (to accommodate the full scope of 24 tactors being actuated) and these units are powered by the aforementioned tactor power supply (4.8V @ 2000mAh) to ensure that they can operate for more than 2 hours of trials. The ground leads of each tactor within a single UNL2803A unit is in series with an output pin of the UNL2803A unit while the V+ supply lead is attached to the tactor power supply. It is also good to mention that these tactors operate at a maximum of 3V, so the voltage supplied by the tactor power supply is dampened by use of a 1500 Ω resistor. The final circuit diagram is shown in Figure 37.

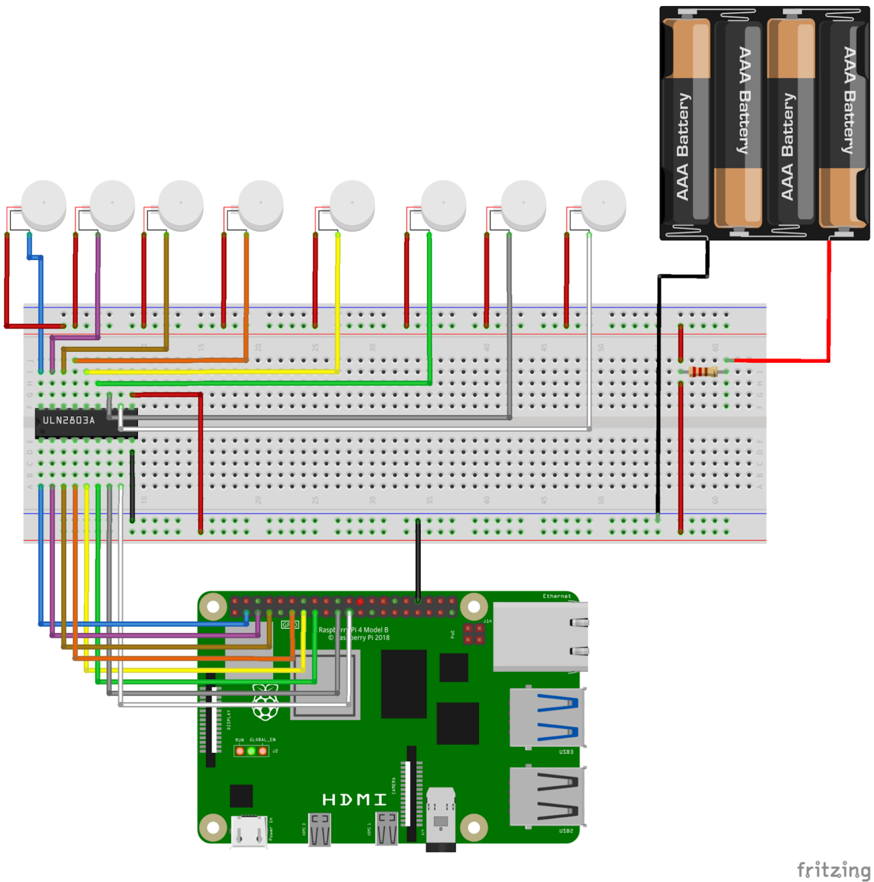


Figure 37: The final circuit diagram which activates 8 tactors using a transistor array and an external power supply. Additional transistor arrays and tactors can be added either in parallel using the same external power supply or with a separate external power supply.

The tactors are powered by a tactor power supply (4.8V @ 2000mAh). This power supply is secured into a pocket attached to the strap with its wires leading into the tactor electronics box. This is shown below in Figure 38.

Figure 38: The pocket on the torso strap that holds the tactor power supply.

Besides tactor components, the torso strap houses components pertaining to the processor mentioned above. This processor comes in the form of a Raspberry Pi 4, and is powered by a 10000mAh power bank. The Raspberry Pi 4 has a specially-made 3D-printed base with stems similar to those on the male tactor housing components at its four that will interface with four female tactor housing components that have been repurposed for processor securement. CAD for the IMU holder can be seen below in Figure 39.

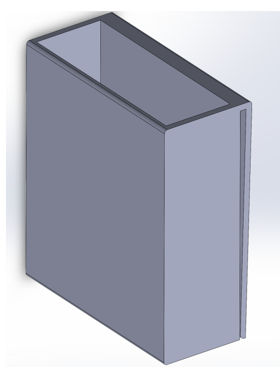


Figure 39: The CAD model of the IMU holder.

Finally, the buckle residing at the end of the torso strap is 3D printed and stitched into the strap material. It can be seen in Figure 40 below.

Figure 40: The 3D printed buckle for the torso strap.

<u>Shin Component Fabrication</u>

The shin component is fabricated in a similar fashion to the torso strap, except it only has two tactors that extend off of the strap and two velcro straps for securement to the device wearer.

<u>Ankle Component Fabrication</u>

The ankle component has no fabrication - it was purchased and ready for use out of the box (Figure 41).

Figure 41: The ankle strap. It comes with a built in mesh pocket to hold the IMU.

<u>Wrist Component Fabrication</u>

The wrist component is the same commercial product (Figure 41) as the ankle component, so it has very little fabrication except stitching of the material to ensure the 95th-5th percentile for wrist sizes are met.

<u>Head Component Fabrication</u>

The head component (Figure 42) only has one fabricated piece, and that is an IMU holder, similar to that used on the torso strap in Figure 39.

Figure 42: The head component (beanie)

Putting on the Wearable Solution

To secure the torso strap to the device wearer, researchers will hold the torso strap to the device wearer with tactors facing towards their torso. They will then feed the strap end through the buckle and loop the velcro back to mesh the male-female velcro straps to one another. The device wearer researchers will then attach the shin component to the device wearer by securing male and female velcro straps to one another. The researchers must ensure that the tactors on the shin component align with the shin and calf of the device wearer to align with the vibrotactile feedback scheme outlined earlier in our report.

Figure 43: (top) strap design detailing posterior and anterior tactors for shin and calf biofeedback respectively. **(bottom)** strap component on device wearer with tactors interfacing with wearer's shin and calf.

Following this, the ankle and wrist components are attached to the device wearer in similar fashion to the shin component. IMUs will be inserted into the mesh pocket on these components.

Figure 44: Wrist strap that comes with a built in mesh pocket to hold IMU.

Finally, the head component is attached to the device wearer, this component is in the form of a hat and only has an IMU holder and IMU attached to it. The hat will be secured to the device wearer’s head, and the IMU holder (subsequently the IMU) will be centered on the device wearer’s forehead.

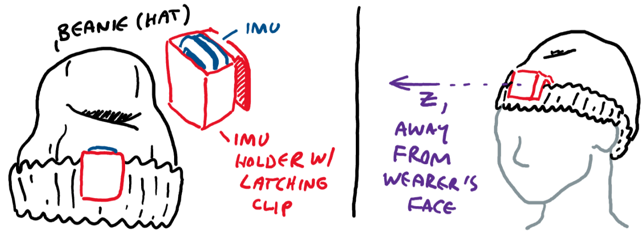


Figure 45: (top) sketch of head component of wearable design solution detailing a hat (black), IMU holder (red), and IMU (blue). **(Bottom)** physical hat of head component.

Figure 46 shows the entire torso strap for the wearable solution.

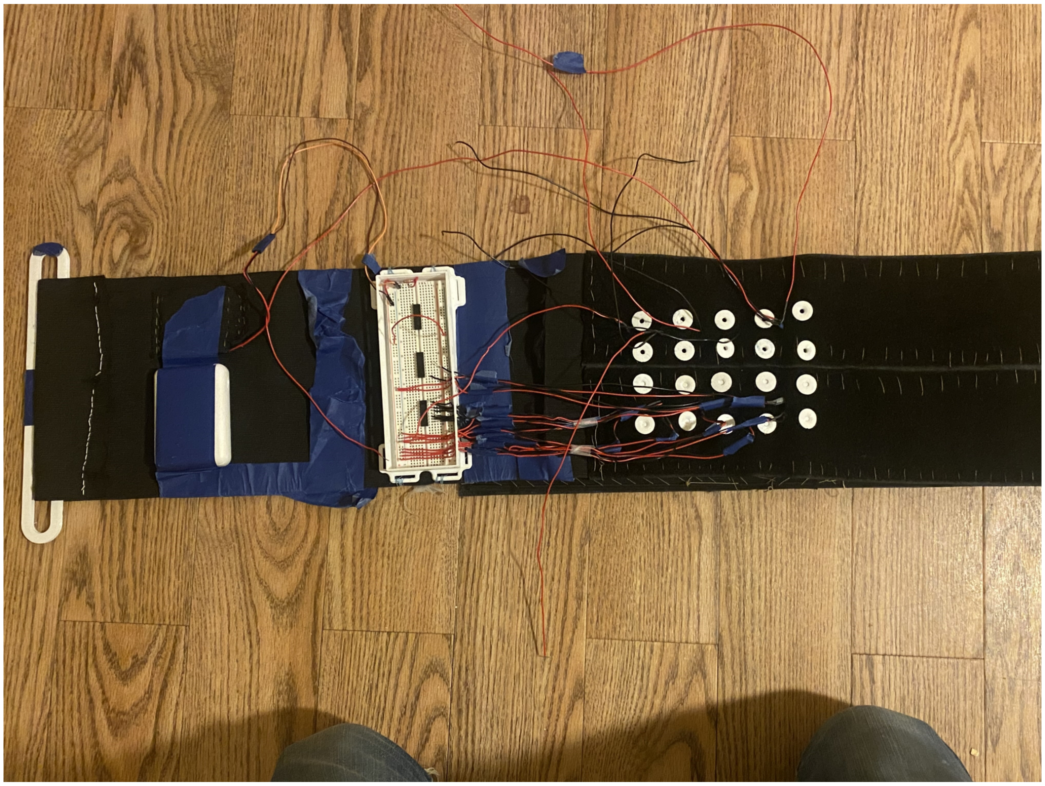


Figure 46: The entire torso strap.

The wearable device that we completed is mainly a proof of concept and is not a full research ready device. The full research ready device has a few additional features that were not included in the proof of concept. The tactor feedback scheme would involve individual tactors on the head, wrist, and both calves, as opposed to two tactors on the leg (front and back of leg near calf/shin) and two tactors on the side torso (right and left side), as was done for the proof of concept. The tactor torso array will also consist of a 5x5 tactor array, while the proof of concept had a 4x5 tactor array. The 5x5 tactor array gives the researchers additional patterns they can develop and provide vibrotactile feedback in. There are additional changes the stakeholders should make for a longer-term device (such as the breadboard, excess strap management, 3D printed components , etc.) that are further discussed in the "Discussion and Recommendations" sections.

Verification

To verify that our design met our specifications, we tested our design against each specification using various verification methods, including demonstrations, physical/empirical tests, and specifications of purchased components.

Wearable. To verify that our design would be wearable, we conducted different empirical tests for each specification because this was the most realistic way to simulate how the device would be used in a research environment. To ensure our design did not interfere with leg or arm swing, we measured the largest point of protrusion for the torso component, wrist component, shin component, and both ankle components. Each strap was almost fully assembled so that we could take into account mounted components in our measurements. We found that the largest point or protrusion occured on the torso strap, where the Raspberry Pi was mounted. The processor protrusion was measured using calipers, resulting in a value of 3.06 cm. This is less than the 3.32 cm threshold set in our specifications, and so this completed our verification. Note that the torso component was missing 14 tactors in the array at this point, but given that the tactors protruded less than the Raspberry Pi, we did not believe that adding the additional 14 tactors would affect our results.

To verify that our full design weighed less than 2.5 kg and was symmetrically distributed around the body, we weighed our design by strap type to determine the total weight of the design, as well as the weight distribution at each strap location. Our overall weight for the design was 1.41 kg, which is less than the 2.5 kg threshold in our specification. The majority of the weight was concentrated on the torso component (1.23 kg) which is located at the center of the wearer's body. The weight is evenly distributed along the length of the strap by the mounted electrical components. The remaining weight from the overall design was distributed to each ankle component, the wrist component, the head component, and the shin component. The ankle components, the wrist component, and the head component all weighed within 4g of each other, whereas the shin component weighs about 3x more. Since the shin component is located in the middle of the leg as opposed to the end of the leg (the ankle), we do not expect the extra weight to cause significant torque that would cause an imbalance in the user. Given this distribution, we concluded that the weight of our design was relatively evenly distributed across the wearer's body and would not impact their natural gait.

Finally, we verified that the IMUs did not rotate more than 11 degrees by simulating a walking trial and measuring displacement of the IMU straps during this period. We first set up each strap on one of our team members and placed the IMUs in their respective mounts. We marked the location and orientation of each IMU on the wearer using masking tape and a marker. Then, the team member wearing the straps walked down a straight hallway in front of the GGBrown Mechatronics Lab for 30 seconds in order to simulate a typical trial envisioned by our stakeholders, which would likely take place in this same hallway. After the 30 seconds ended, we marked the new location of the IMUs and measured the displacement. We noticed that the wrist component and one of the ankle components did not move during the trial. The other ankle component moved down the wearer's leg by 0.5cm, but did not rotate. For these components, we concluded that the lack of rotation fulfilled the 10 degrees threshold set by our specifications. Some limitations of this experiment include that the IMU holder for our head component had not been 3D printed by the time of this trial, and so we were unable to incorporate it into the experiment. Additionally, our torso component did not have a management system for the additional strap material that occurs when the design is used by a wearer with torso dimensions less than our largest target user (details in Accommodates Variety of Users). Without the strap material management system, the excess strap material hangs unevenly from the wearer's torso and pulls down a section of the torso component, to the point that the wearer needs to hold the material. In a real trial, the wearer should not have to hold the torso component up, and so this component did not pass our verification. Though our proof of concept did not have a method for managing the excess material by this point, our final design would have clips, buttons, velcro, or some method of securing the excess strap material. We recommend that the stakeholders reattempt this verification process once the excess torso strap material is managed to determine if it meets the 10 degrees of rotation threshold.

Accommodates Variety of Users. To verify that our design could be worn by fifth to ninety fifth percentile of people with different heights and weights, we measured the prototype using a tape measure and a ruler to make sure it was suitable for that population. Due to time constraints, we selected the simplest verification method to determine that the device would be wearable for people of different sizes and shapes. Since no physical testing was done to verify that the device would fit people with lower or upper limit of the specification, the design is only verified theoretically to fit people between the 5^{th} and 95^{th} percentile of sizes. Therefore, further physical testing is needed for a more complete verification. The restriction of the device for it to fit the wearers of height between 149.8 cm to 187.4 cm was the length of the wire from the leg to the processor. We determined that the wire length needed to be at least 110 cm for the tactors on the leg and 80 cm for the tactors on the torso. We verified that the specification was satisfied by measuring the length of the wire. The specification for the head circumference was from 51.9 cm to 60.0 cm. We verified, by measuring, that the head component that we purchased fits head circumference of 37 cm to 70 cm. To fit the waist circumference of 73.3 cm to 132.6 cm, we verified that the torso component can be worn by people with waist circumference of 70 cm to 135 cm by measuring the entire component length with a tape measure. For the calf component, we verified that the specification of calf circumference from 31.8 cm to 47.1 cm was satisfied by measuring the calf component which ranged from 31 cm to 48 cm. Lastly, to verify that the wrist component meets the specification of 13.8 cm to 19.1 cm of wrist circumference, we verified through the length measurement that the wrist component could fit people of wrist circumference from 13 cm to 20 cm.

Semi-real time Feedback. To verify that our design could provide wearers with semi-real time feedback, we addressed each specification individually. To verify that our design provided vibration frequencies between 220 Hz - 300 Hz, we studied the VPM2 Vibrating Disk Motor specification sheets. From the data sheet we identified that at 3 V, the motor rotated at 12000 rpm. Using the linear relationship between voltage and motorspeed [50], we determined that at 3.11 V the motor speed was 15027.3 which was approximately 250 Hz. To ensure that wearers of our design could distinguish vibrations between tactors, we drew a 5 by 4 grid on our strap design as a template for our 20 tactor array. This allowed us to plan for our design to have a center-to-center tactor distance of 30cm on the strap. Once we mounted tactors on the drawn locations, we measured the center-to-center distance of the tactors to confirm that they met specifications. To verify "Able to process data and power equipment for ≥ 2 hours," we chose to activate the user interface on the Raspberry Pi for 2 hours and run data collection trials. Our stakeholders informed us that a typical trial will last 30 seconds, but a session with one research participant could last 2 hours. Therefore, we wanted to confirm that the server could run for 2 hours straight to simulate a session, and that it could collect data for 30 seconds throughout that time frame. To verify this, we kept the server running for 2 hours and activated four IMU sensors for 30 seconds at three different times: once at the beginning of the session, once at the 1 hour mark, and one at the 2 hour mark. This would allow us to confirm if the server was functioning for the full 2 hours, and that there would be no issues with running a typical 30 second trial multiple times throughout. Data was successfully collected from each IMU for each trial during this test run. Lastly, we verified that the range of connection between the processor and UI was ≥ 5m by using VNC Viewer. This program allows the researcher to control the Raspberry Pi desktop remotely, and thus gives the researcher access to the user interface without requiring a wire from the Raspberry Pi (located on the wearer) to the laptop. To verify the range, we stood 5m away from the Raspberry Pi and attempted to initiate a remote connection with VNC Viewer. Once a connection was established we activated the user interface, connected an IMU to the Raspberry Pi, and collected data.

Data was successfully collected and saved on the Raspberry Pi through this method, thus verifying that the range of connection was successful at 5m. There were some limitations to this method, however. This trial was performed using a team member's personal wifi network. At the time of this verification we were unable to connect the Raspberry Pi to a University of Michigan wireless network, such as MWireless or Eduroam, and so we were unable to test this process on campus. This is a limitation, as future use of our design would primarily occur on campus. While we are confident that our design meets our specifications, we are not very confident in getting our device working on MWireless. We have been in contact with Michigan IT, but we are providing our stakeholders with a number of options to address these concerns.

Kinematic Data Measurements. To verify that our device could properly measure and record kinematic data, we ran multiple tests focused around our IMUs and the requirements and specifications in this category. Before beginning the verification testing, we needed to ensure that when data collection was started, IMUs started to record data at the same time due to the Xsens server limiting timestamp synchronization. The provided Xsens server does not allow for timestamp synchronization while live-streaming data so we needed to confirm that all IMUs started taking data at the same moment even if the timestamps didn't match, as this could be fixed in the post-processing if needed. The test procedure that we chose to conduct started with four IMUs plugged into a slot in the IMU charging case. Note that one of the IMUs was with another team member so only four IMUs were tested. By plugging in all of the IMUs in the charging case, it would allow the IMUs to move with the same relative velocity if the case was moved around. This charging case was aligned to the edge of a 30 cm ruler so that the case could be slid in a linear path along the ruler. The IMU y-axis was parallel to the straight edge of the ruler. We began by logging data while the IMUs were stationary before sliding the entire case along the ruler for 15 cm. After the trial was complete, we plotted each IMU's y-axis acceleration against their respective timestamp. The results of the test are shown in Figure 47.

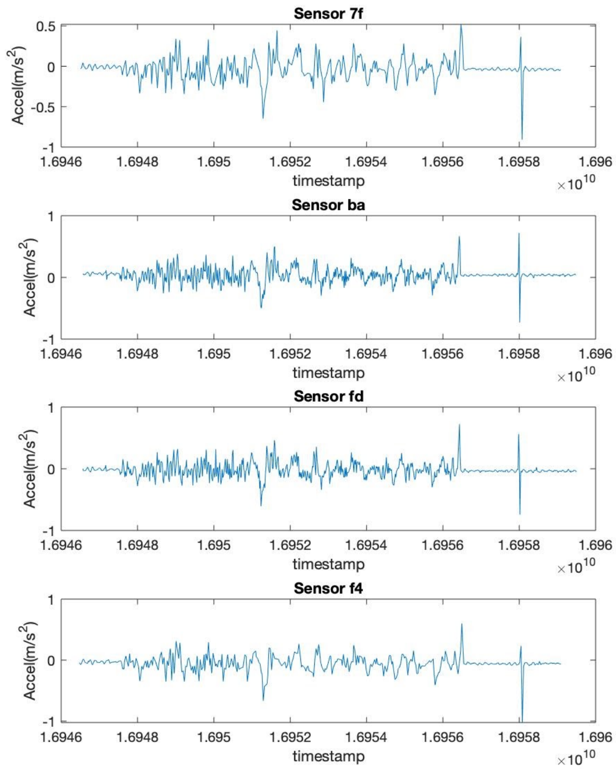


Figure 47: Results of data synchronization tests with four IMUs.

Our first specification was that 5 IMUs are played on each leg, the head, the trunk, and the wrist, and we could test and verify that by simply ensuring that our design was capable of holding IMUs at these locations with straps. Our next specification was that our device was able to process at least 5 signals. To verify this, we turned 5 separate IMUs on and, through our Raspberry Pi and recording algorithms, measured and recorded data with all 5 attached to the body (right ankle, left ankle, wrist, forehead, and lower back) while a team member walked at their own pace. We looked at the resulting data from this test and verified that each IMU was collecting data independently and successfully. We were also able to verify that the data was tracking kinematic data motions as expected. Here, we show the acceleration in the x, y, and z directions from the IMUs located on the lower back (Figure 48) and the head (Figure 49). The data shown is a 5 second sample pulled from the longer test sample. For the lower back and the head, the data is compared to data published for healthy young men walking. To align with the published literature and the coordinate system of the Xsens DOT IMUs, the x-direction corresponded to the vertical (VT) direction, the y-direction corresponded to the medio-lateral (ML) direction, and the z-direction corresponded to the anterior–posterior (AP) direction.

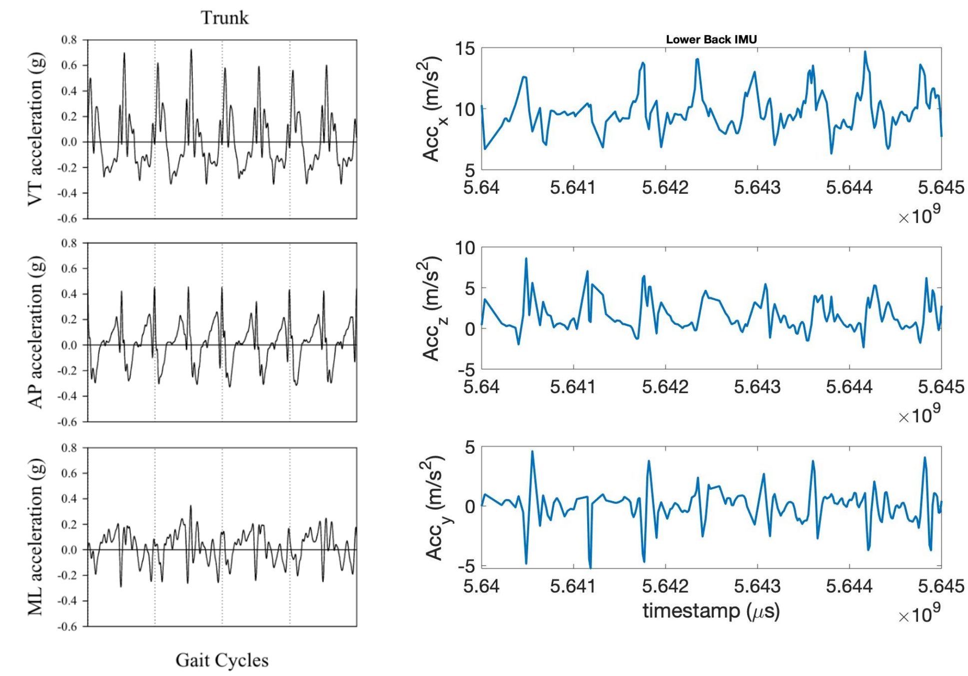


Figure 48: (left) [51]**:** Published acceleration of the trunk of healthy young males walking. (**right):** Our acceleration of the trunk of a team member walking.

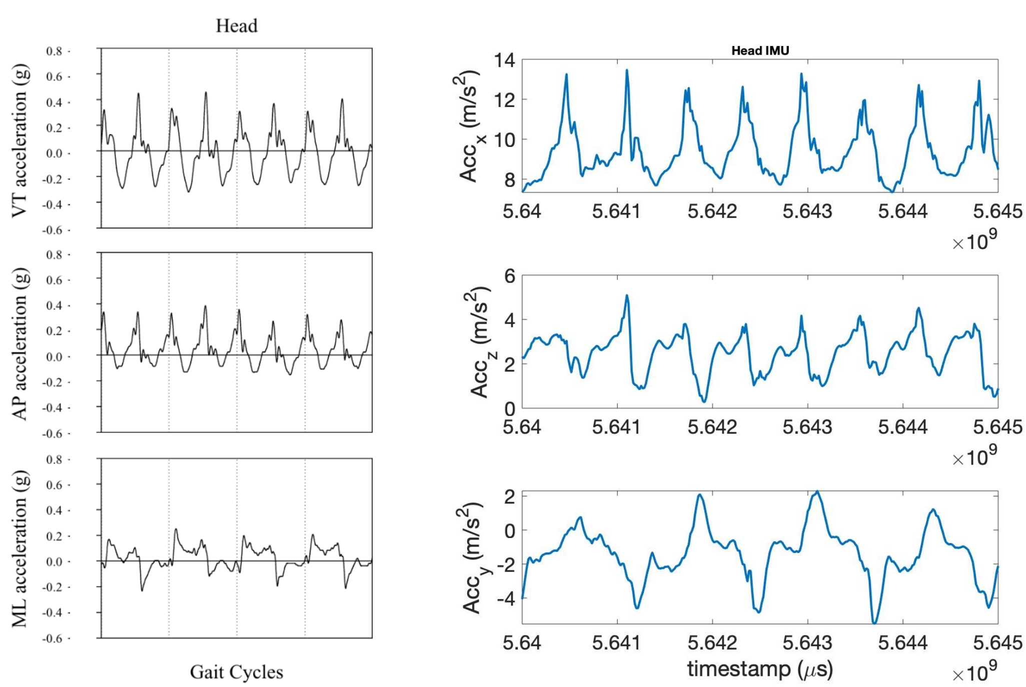


Figure 49: Left [51]**:** Published acceleration of the head of healthy young males walking. **Right:** Our acceleration of the head of a team member walking.

Comparing our IMU acceleration data (with no post processing) to published acceleration data for the trunk and the back, we are confident that our device is capable of capturing gait kinematics. The general shape and peaks of accelerations for our data were similar to that of published data, but we recommend our stakeholders do additional testing to confirm that the IMU recorded gait kinematics match as expected with all of the post-processing that will likely lead to a better comparison with the published data.

For our next set of tests, to study that our device could receive and process data in semi-real (≤ 2 seconds) time, we connected vibrotactors to our microprocessor, taped IMUs to our bodies in various positions, and performed known motion with the limbs attached to the IMUs. An example of one test was to tape the IMU to a hand and move it in a chopping motion to test the gyroscope and rotational motion detection of the IMU. The data is streamed over Bluetooth every 0.1 seconds (the streaming speed can be adjusted by the researchers). During the test, the tactors vibrated practically instantaneously when the IMU readings were over the predetermined threshold. Since we did not have a way to see the data fast enough to time this manually in real time, after the motions were performed, we recorded the amount of time it took for the vibrotactors to react after the perceived motion, and were able to verify that this time was, indeed, consistently under 2 seconds. For our last two specifications, referring to the sampling frequency and range of the IMUs, we were able to verify these with the spec sheets from our IMUs via the Xsens DOT website, allowing us to see that our IMUs were fully capable of meeting our needs in these areas. The Xsens DOT IMUs sample at 800 Hz and have an accelerometer range of ± 16g and a gyroscope range of ± 2000 °/sec.

Vibrotactile Feedback Display. To verify that our device had a proper vibrotactile feedback display, we did multiple physical tests to verify that our device had multiple outlets of vibrotactile feedback. For our first test, to verify the specification around requiring vibrotactile feedback to 5 separate locations, we placed vibrotactors on the legs, head, stomach, and wrist over varying thicknesses of clothing (ex. Jeans, thin t-shirt, thick t-shirt, and socks) as well as directly to the skin to ensure that the vibrations could be felt. We conducted a similar process to verify our second specification, requiring the patterned array of tactors on the stomach, by testing varying patterns through different coverings to ensure that both the vibrations as well as the differentiation of vibration patterns could be recognized. While all of the tactors could be felt, by inspection, our final design only provides feedback to two tactors on the leg, two tactors on the sides of the torso, and 20 tactors in the torso array. With additional time and equipment, we are confident that expanding our design to include all feedback locations will be successful.

Interactive Researcher Interface. For the researcher interface, our design needed to be able to control testing parameters (specific tactor activation, number of sensor signals collected) every 30 seconds and have the trial settings, IMU data, and tactor on/off times saved to the researcher laptop every two hours. We verified our design achieved these through demonstration to show that our design is capable of allowing researchers to change and save testing parameters. A session consisting of 3 unique trials (15, 30, and 45 seconds in duration) was completed. The session was run by a team member with limited exposure to the inner workings of the user interface so they had to rely on the provided documentation on how to run a session. At the beginning of each trial, the team member selected a different option for the "Tactors in Use" setting (first, they selected the torso array, then the leg tactors, then the side torso tactors) and a different option for "Data processing" scheme (first trunk sway, then heel strike for the next two), which represents different combination of sensor signals. The team member started and stopped data collection via the researcher interface. They were able to change the settings in between each trial to prove our design allows the researchers to change settings every 30 seconds. Our design actually has no restriction for time between changing the settings; they can be changed at any point except in the middle of data collection so we have verified the first requirement. Our demonstration also verified that our design saves the trial settings and IMU data to the Raspberry Pi every two hours but not the tactor on/off times. Our design saves the information immediately after a trial so we have partially verified the second requirement. Since our design allows the tactor on/off times to be identified and saved, but does not actually save the tactor on/off times, we could not fully verify this requirement. Saving the tactor on/off times can be a feature that is added in a future design iteration. Since this demonstration was done by a team member following the provided documentation, we are confident that our results reflect how the design will perform when given to our stakeholders.

Easy to Set Up. To verify that our design could be set up on a wearer in less than 10 minutes, our team practiced setting up the design on ourselves. Two members of our team, David and Kai, practiced setting up the straps on themselves, which were fully assembled with tactors and IMUs. Straps were fully assembled with tactors, IMUs, and electrical components beforehand because we assumed that the researchers will have already decided which tactors to use and what body segments they want to track before beginning a session with a participant. By rotating who was setting up the device, we were able to capture a range of user perspective and methodology for attaching the device on a wearer that would impact the timing of set up. Each attempt was timed, where David spent 3 minutes and 19 seconds assembling the straps and Kai spent 1 minute and 30 seconds. The results of this procedure show that our device can indeed be set up in less than 10 minutes, meeting our first specification for this requirement. Additionally, it is important to note that each team member spent the most time putting on the torso and the wrist strap, so we recommend that during a real session stakeholders should assist their participants in securing these components. Some limitations of this verification include that we mainly considered the situation in which participants would be setting up the device on themselves. Additionally, we assumed that the wearer would receive an explanation of how to set up the straps beforehand. It is possible that the researchers will choose to be the ones who set up the straps on the wearer. However, we believe that the difference in a wearer versus a researcher setting up the straps will not have such a large impact on the set up time that it would exceed 10 minutes, and it is possible that it would take the researchers even less time given that they will have more practice with the process as they continue use of our design.

We were able to verify the specification “less than 10 minutes to calibrate IMUs” by referring to the Xsens DOT website. Each sensor comes factory calibrated, and so there is no need/no formal process to calibrate the IMUs after purchase. Therefore, since the IMUs will not need to be calibrated during each session, we verified that it will take less than 10 minutes to calibrate the sensors.

Easy to Clean. To verify that our device is easy to clean, we practiced cleaning two different materials involved in our design. To determine if our fabric components could be cleaned by water/detergent in less than 12 hours, we practiced washing the straps of our design in an at-home washing machine. A standard washing machine was used to clean the straps on the delicate cycle with cold water. The straps were then dried in a standard dryer on the delicate setting before being let to air dry for an additional 2 hours. The process of washing the fabric took 3 hours 23 minutes, falling within our 12 hour time range. For the electronic components, we took an Instant Fresh and Clean Antibacterial wipe and wiped the IMUs, tactors, and Raspberry Pi case. This process took 58 seconds, falling within our 2 minute time range.

Based on the verification testing for each specification, we are confident that our design will meet our stakeholder specifications and the design will be able to be used as a research tool after a few modifications as previously discussed. The stakeholders should complete those modifications to make the device a research ready tool and then replicate the verification tests that our team was not able to simulate in a real-life sense ("Accommodates a variety of users," "Kinematic Data Measurements," etc.).

Validation

For our validation testing, we attempted to look at our design as objectively as possible to see how well we met the original problem surrounding the implementation. To begin this testing, we took one of our team members, who was not familiar with implementation of the UI, go through the setup process as described in an "instructional guide" of sorts. From beginning to end, we found that, without much prior knowledge of the setup, they were able to fully understand and begin running trials with our device with the IMUs and tactors turned on. From here, we performed a few of these setups and had multiple of our team members take turns walking around with our device to track their motion with the IMUs. We looked at the data resulting from these tests and were able to validate that the motion tracked reflected common body motion shown from other research (Figure 48 and Figure 49). We also tested our tactors over various pieces of everyday clothing to ensure that they could still be felt and that certain patterns on the stomach could be differentiated from other patterns.

Before putting our device on a test subject, a few things must be done. For starters, our current device implements a No-Solder breadboard to make the connections between our microprocessor and our tactors. Although this does work functionally, it is a little messy and unreliable for longer and more in-depth testing. There is also a potential for exposed wires. Therefore, this needs to be replaced with a more permanent solution before running actual trials with test subjects. In addition, our device currently has trouble connecting the Raspberry Pi microprocessor to the internet of the school, a key element for allowing our device to stream data over wifi. We are currently in talks with the University of Michigan IT department to try to get this to happen. Furthermore, what is probably the most glaring flaw of our device is that it lacks the algorithms to process the gait of the individual. Our device can track gait and can give feedback to different tactors, but before any testing can be done to assess if the device actually helps correct the gait of people with vestibular disorders, we need the algorithm that process this data from the perceived motion, and then compare it to specified standards and allow for feedback based on the algorithms. This was not in the scope of our project, but these algorithms still must be added by our stakeholders before our device can be used for actual testing.

For our stakeholders, we think there are a few different sets of tests that they can do to confirm that our device meets their expectations. The first set of tests focus around the UI. Most of these tests are simple overviews; for example, they can make sure that all the different movements they wish to perform are in the UI, that all the different places they wish to give feedback are there, and that the UI can update the settings of a trial successfully. The second set of tests have the do with the physical components of the device. These kinds of tests involve mostly putting on the device and testing its components. For example, the researcher should put the device on themselves and perform all the motions they wish to run in trials for people with vestibular disorders to make sure that the device is comfortable, safe, and collecting the right kinds of data. They can also practice washing the devices as well as attaching and unattaching various components so that they can play with the customizability of the device. The third set of tests have to do with the tactors. These kinds of tests are about both the functionality of the feedback as well as the connectivity of the tactors themselves. Initially, all the tactors should be run individually as well as in all common patterns that would be done during a normal trial, this both to ensure that the correct tactors are turned on as well as that no tactors are overall failing to perform. Then, this can be combined with the tests of the physical device where the researcher can put the device on themselves and perform all the motions of a normal trial, varying their gait from normal to abnormal to see if the tactors turn on when they should and don't turn on when they shouldn't.

Before the device is put on test subjects, though, the stakeholders should get this device approved through a research review unit to ensure that the device can safely be used in a research setting. The stakeholders should also run trials with themselves performing known movements to ensure that the tactors are properly providing feedback, the IMUs are properly recording data, and the recorded data is as expected for a specific movement. If all of these tests are performed successfully with expected data, without damage to the device or the wearer, and with correct feedback, then the device should be deemed ready to run for trials with test subjects.

Discussion and Recommendations

Based on our experience working on this project the entire semester, our team has learned throughout the process and would re-do certain aspects of the design based on what we have learned. We would order our components sooner than we initially did. We started to run out of time to put our design together and do all of the testing that we wanted before turning the design over to our stakeholders. Had we purchased components earlier, we would have had more time to build and test and also likely would not have experienced some components being out of stock.

In the current state, our physical prototype demonstrates a proof of concept for a customizable wearable vibrotactile feedback display for gait biofeedback research tool. Our presented concepts show the full design that we recommend our stakeholders continue with a second iteration of our design. The main differences between our proof of concept design and the final research ready design are discussed below with specific ways we recommend our stakeholders consider for completion of a research ready design.

Our design of the researcher UI enables the UI to be easily scalable to include additional settings/options or modify existing settings/options as the project evolves. The current implementation gives the researchers a good starting point for trial settings and allows new data processing schemes to be created directly within the UI further making our design customizable and reconfigurable. Since the data processing schemes are saved in a consistent json format, that also allows for easy scaling of future data processing applications. The UI also does not require experience with programming to use. The UI is started and stopped with one line in the terminal and the terminal does not have to be touched during a subject (unless something goes wrong, then the researcher is instructed to run the one line to turn the UI off and back on). The UI can also be expanded to other applications involving IMU data tracking or biofeedback, such as athlete data tracking and body kinematics beyond those with vestibular disorders.

The UI also has some limitations in the current implementation. Some of the work for creating a data processing scheme must be done manually, such as moving the json file containing the new data processing scheme information, creating a new radio button in the UI, and updating various statements in the data processing program. We don't anticipate this being an issue during a session with a subject because all of this work can be done upfront. The researchers can create new data processing schemes and make the manual changes outside of a session. The UI also cannot re-process settings that have been changed without first starting data collection. If the settings are changed after the "Update Settings" button is clicked, the data processing script must be manually restarted and the downloaded file must be manually deleted. A simple fix for deleting the downloaded file would be to implement a new button in the UI to delete the file when clicked. More broadly, all of these manual tasks should be automated in future iterations by restructuring the provided shell scripts and implementing new features into the javascript that allow access to local storage. Using the shell scripts will also allow the data processing script to be simplified to only process IMU data and activate tactors.

In future iterations of the UI, we recommend adding a control signal input box and implementing more complex data processing algorithms that will allow for more specialized biofeedback applications. As the project evolves, additional tactor activation patterns, tactor activation locations, and additional data processing schemes should be added to the UI and the data processing scripts. The IMU display can also be changed to easier identify each IMU. The current method uses the last two digits of the IMU name, but the text color in the UI can be changed with a corresponding colored sticker on the physical IMU for easy identification.

As for the physical components of our design, we have succeeded in creating a device that is very customizable; it can successfully be put on people of different heights, waist sizes, and many more different sizes and shapes via the adjustable straps. It is also customizable in means of feedback as it can provide feedback to different locations but also is able to be changed where these locations are. The current design is meant for giving feedback to the head, wrist, legs, torso, and stomach, but the possibilities are nearly endless with the only true additional component being tape or a simple strap to put a tactor elsewhere.

However, the device is also physically limited in some aspects as well. One con of our design is that the straps and connective parts are all individual. This could be a problem as some could get lost or misplaced from the others, but the biggest issue we see is the consistent placement of each individual component over different trials. Specifically, it is going to be difficult to place the leg strap on the EXACT same spot of the leg for each trial, the same being for the other components as well, and because our design has these components that must be placed individually (as opposed to some kind of body suit or more-body morphing, ultra-connected design), the consistency of data collection between trials might be affected unless incredible attention is paid to the placement of each component.

Beyond the user interface and Raspberry Pi, general pros of our overall design include its ability to track motion from multiple body segments. The 5 IMUs in the design can be placed anywhere on the body, giving researchers the ability to control what body motion they want to collect data from in order to provide feedback to the wearer. Additionally, researchers can control which tactors activate depending on thresholds they set for different IMU readings (such as acceleration in the x direction, etc.). The wearable features of the design itself can also be adjusted for different body sizes. The straps were designed to fit body sizes from the 5th to 95th percentile of human body sizes by using elastic material and velcro to secure the design at different dimensions. Lastly, researchers can access the user interface and control the processor wirelessly from their own computer using VNC Viewer. This wireless connection reduces the amount of wires required to access the processor display, and enables researchers to monitor data collection during a trial. However, as mentioned in the Semi-real time Feedback verification section, this functionality does not work on university wifi and will require additional support from U-M ITS.

In terms of general cons, our design currently requires two power supplies — one for the Raspberry Pi, and one for the tactors — which adds weight to our design. We selected two power supplies based on the theoretical power analysis we conducted in the Engineering Analysis section. Given time constraints, we did not want to risk purchasing a single power supply in the case that it failed to provide power to our entire design, by which point we may not have time to purchase another. Therefore, we chose two separate power supplies that we were confident could power each sub function for our proof of concept. In the future, we recommend finding a single power supply that can support the Raspberry Pi and 30 tactors in a final design. Additionally, our design has at least 24 wired connections for the tactors as we could only find wired tactors during our product research. This makes wire management difficult, and can contribute to motion impediment, a complicated set up process, and an overall clunky design. We recommend that either wireless tactors be used in this design or a more robust wire management system be implemented, such as shortening wires or zip tying groups of wires together. Another con is that our proof of concept currently supports 24 tactors, whereas our final design/specifications require 30 tactors. To expand the amount of supported tactors, an additional component called an expansion board will be required. Finally, our design currently uses a No-Solder breadboard. We recognize that No-Solder breadboards do not have secure connections, and it is very possible that wires will pop out of the breadboard and lose connection while the design is in use. We recommend that this No-Solder breadboard be replaced with a solder-able breadboard, which will provide a more secure connection. If researchers still want the ability to easily remove tactors, jumper wires can be used with the soldered wires.

We also have several recommendations for improving the functionality of the Raspberry Pi. Currently, the Raspberry Pi has an external button to disconnect power. However, disconnecting power without safely shutting down the Raspberry Pi carries risk of corrupting the SD card and thus, all of the programs on it. Setting up an external button that initiates the shutdown process of the Raspberry Pi would help prevent this issue, and is highly recommended that it be implemented. Finally, though our Raspberry Pi is capable of connecting to the internet via a team member's personal wireless network, at this moment in time we have yet to successfully connect the Raspberry Pi to MWireless or Eduroam, as there is an issue with DHCP activation. Internet access is important for our project, because it enables the use of VNC Viewer, which is a program that allows you to remotely access and control the desktop of the Raspberry Pi. Currently, a team member is working to redownload the Raspberry Pi OS onto a separate SD card, as recommended by U-M ITS, to determine if a complete reboot of the system will disable whatever may be interfering with the internet connection. The original SD card with our researcher UI is saved and will be given to stakeholders during the handoff of our project. If a successful wifi connection cannot be made between the Raspberry Pi and the University of Michigan wifi networks, we have several recommendations. The first thing we recommend is getting in touch with U-M ITS. Our team will send our stakeholders the contact information of the ITS employees that are familiar with our issue so that the troubleshooting process can pick up where we leave off. If the Raspberry Pi cannot connect to the university wifi after this, our stakeholders can look into purchasing a wifi dongle for the Raspberry Pi and turning it into a wifi access point. Creating a wifi access point essentially forms a wireless network that other devices, such as the Raspberry Pi and a laptop, can connect to. This wifi access point will not actually provide any internet to the other devices, but VNC Viewer only requires that the laptop and the Raspberry Pi be located on the same wireless network and thus, an internet connection is not necessary.

Finally, our wearable aspects of our project come with some pros and cons as well. For a pro, the tactors can easily be attached/removed from housings while maintaining resistance from removal during trials. However, given that none of our team members had experience with sewing before this project, the stitching on each strap is roughly done and not completely secure, and the insertion of the female tactor housings has broken a stitch securing the velcro strip to the torso strap. For future design iterations, we recommend that the stitching for the securement of the velcro strip to the torso strap be redone using a sewing machine, or by someone with intermediate sewing experience, to ensure the stitching lines do not come near to the slits in velcro and strap reserved for the female tactor housings. We also recommend mounting the breadboard (or more permanent replacement for a breadboard) to an external fixture that can then be attached and detached from any surface without fear of adhesives damaging the main electronics. Additionally, we did not have time to create a secure management system for the excess torso strap material required to accommodate body sizes from the 5th to 95th percentile. We recommend that clips, buttons, or velcro be used to create a method for managing excess strap material. We also suggest that some of our 3D printed components be replaced with a more robust, commercial product to withstand frequent use during research. This includes components such as the torso strap buckle and the breadboard mount. Finally, we suggest that our stakeholders consider purchasing higher quality tactors for long-term use. We have had issues with wires breaking off from the tactors during assembly, which have required soldering to reattach. Though the VPM2 is a good purchase for an early prototype, tactors with more wire attachments would be more reliable for future iterations.

After improvements have been made to our current prototype, we hope to see our stakeholders create a more complex data processing algorithm to interpret IMU data and provide vibrotactile feedback. This was out of scope for our project, but the full functionality of our design would not be complete without this post-processing software.

Conclusion

This report discusses the problem background, design requirements and specifications, initial concepts, engineering analysis, final solution and verification of our project which is to design a customizable wearable vibrotactile display for gait biofeedback research. During this process, we utilized several different information sources such as stakeholders, the University of Michigan library and relevant literature. Among these sources, stakeholders, Prof. Kathleen Sienko, Safa Jabri, and Chris DiCesare, played an important role in helping us iterate the process of defining the problem and developing and refining the requirements and specifications. To maximize the effectiveness of the aid from the stakeholders, we devised a stakeholder engagement plan which includes regular meetings, feedback, and organizing questions and concerns before each interview. Through stakeholder engagement, we were able to generate most of our design requirements which include being wearable, having an interactive researcher interface, being able to wirelessly communicate, and more. Engineering specifications were generated from stakeholder interviews and extensive research by reading relevant literature.

After establishing and referring to the requirements and specifications, we generated and developed design concepts. Utilizing functional decomposition, brainstorming, and morphological analysis, we generated numerous potential combinations of design concepts. From the total number of combinations, we selected three overall designs for a more in-depth assessment. Then, through the use of a decision matrix, we determined one design concept to further refine and develop. The selected concept consists of wireless IMUs and wired tactors attached to elastic straps. Also, the concept features rechargeable IMUs and a portable power pack and batteries for the processor and the tactors respectively, and utilizes a laptop for an interactive researcher UI. Our main goal in generating, developing, and selecting this particular concept was to not only meet the stakeholder requirements, but also to be inclusive for people of all sizes, shapes, ethnicities, sexes, races, background, and ages.

After concept selection, we spent time discussing with our stakeholders to refine and improve the chosen design concept. The changes included tactor location and orientation to enable explicit feedback on the lower body, wire management, and strap design. Following the evolution of the concept, we identified design drivers that needed to be addressed that were specific to our selected concept. The design drivers asked questions that were crucial for solution development such as component selection, Wireless connection, processor configuration, and power consumption. Through various types of engineering analyses such as product assessment, theoretical calculation, and empirical testing we were able to answer the design drivers. Furthermore, we conducted a risk analysis in which we identified safety hazards and failure risks for the wearer and the device respectively. Finally, after referring to the requirements, specifications, and design drivers, we designed our final solution.

After designing our final solution we conducted numerous tests to verify that our solution satisfies the specifications. We conducted physical tests such as measuring dimensions and weight of components, and put the device on our body to ensure that it was indeed wearable. We also tested the physical components by activating tactors, washing the fabric material and drying it. We conducted tests to ensure that the IMUs collected kinematic data as planned, and that the researcher UI processed the collected data and displayed it appropriately. The above tests verified most of our specifications, and indicated that our generated solution was adequate for proof of concept.

After assembling the prototype and conducting verification tests, we critiqued our design according to the test results. One advantage of our solution was the highly customizable physical components. Another one was a scalable researcher UI. A major disadvantage was due to high customizability, there were numerous individual components which could be misplaced. Also, because it was only the first iteration of the researcher UI, the data processing was done manually. For future iterations we recommend implementing a more complex data processing algorithm, improving the finish/material of the physical component, and expanding the scope of the design to better satisfy the researchers' needs.

Information Sources

We used two main sources for information gathering and research: interviews with stakeholders and literature from the University of Michigan library. Interviews with stakeholders provided initial problem background and design requirements that we could further develop and refine. Literatures such as research papers and patents provided background knowledge on the subject matter and helped generate engineering specifications.

The stakeholders for this project include Prof. Kathleen Sienko, Safa Jabri, and Christopher DiCesare from the Sienko Research Group. From the early stages of the project, we conducted several interviews with the stakeholders to gain information on the problem background, previous research, and design requirements. The stakeholders suggested relevant literature [4,52] from the Sienko Research Group's previous research regarding static balance biofeedback systems that provided us with context and a direction of this project.

We met with the University of Michigan biomedical engineering librarian Joanna Thielen at the beginning of the project to receive advice on navigating the University of Michigan library web portal to find literature relevant to the project. She initially suggested research papers that could help kickstart the project, then took us through the library website and demonstrated how to utilize it to its fullest potential. To find more information needed to develop engineering specifications, we used Scopus, a search tool that contains engineering and medical literature. Moreover, we found several patents that we used for benchmarking through Espacenet, a patent searching tool. Lastly, we searched for engineering standards for design guidelines through the database for standards.

Authors

Do Hyun (Stu) Lee is originally from Seoul, South Korea. He is a senior mechanical engineering student. His interests are design and manufacturing. After graduation, he hopes to pursue a career in the medical or the automotive industry. In his free time, Stu enjoys cuddling and playing with his dog Oreo.

Kai Myran is originally from Landenberg, PA. She is a fourth year student studying mechanical engineering with a strong interest in Design Science. After graduation, she hopes to continue her education through a Master's degree program in mechanical engineering. Apart from academics, she enjoys hiking, crocheting, and spending time with her dogs. She is also treasurer for the University of Michigan American Society of Mechanical Engineers.

Kristina Nunez is originally from Riverview, MI. She is a fifth year student studying mechanical engineering with a minor in computer science. Her interests include controls, mechatronics, and robotics. After graduation, Kristina will be working as an engineer in the automotive industry. In her free time, Kristina enjoys cooking, playing board/card games, and watching hockey or any Michigan sports. She also captains the University of Michigan Women's Ultimate Frisbee Team.

Brady Oosse is originally from Grand Rapids, MI. He is a fourth year student studying mechanical engineering with a minor in computer science. He enjoys coding, doing research, and taking on organizational/leadership roles during projects. In his free time, he enjoys lifting weights, exploring Ann Arbor, and watching any sporting events that include his namesake, Tom Brady. After graduation, Brady plans on joining a leadership rotational development program in a professional manufacturing environment. He is also the host and president of the organization/reality TV show "Survivor Michigan".

David Wells is originally from Chicago, IL. He is a fourth year student studying Mechanical Engineering with a minor in Electrical Engineering. He enjoys drawing comics, riding his bike, sculpting, and playing competitive online games in his spare time. His interests within the engineering space lie with rehabilitation, and post-graduation he plans to apply his education to create solutions that restore independence in the lives of many with disabilities.

Acknowledgements

This project would not have been made possible without lots of help and feedback from our peers as well as faculty members of the University of Michigan. We would first like to thank Professor Kathleen Sienko for being both a wonderful mentor, professor, and stakeholder who was constantly working with us by helping us improve our design and pointing us towards resources to further our knowledge of the subject matter. We would also like to thank Professor Alex Shorter for meeting with us multiple times throughout the semester to help perfect and critique some of our presentations. To Safa Jabri and Chris DiCesare, we want to thank them for consistently working with us to help understand the process of the research being done as well as meeting with us weekly to critique our final prototype. We would also like to thank members of the Michigan IT and Library departments for helping us fix connectivity issues with our device and help us find more and more research papers respectively, and specific thanks to Joanna Thielen for teaching us how to use the University of Michigan's "SCOPUS" software. Finally, we would like to thank all the members of teams 6, 8, 9, 10, and 11 from ME450's 2021 winter term for giving us feedback on our presentations and helping us think through a lot of our problems from an objective standpoint.

References

[1] Agrawal, Y., Ward, B. K., and Minor, L. B., 2013, “Vestibular Dysfunction: Prevalence, Impact and Need for Targeted Treatment,” J. Vestib. Res. Equilib. Orientat., **23**(3), pp. 113–117.
[2] Fujimoto, C., Suzuki, S., Kinoshita, M., Egami, N., Sugasawa, K., and Iwasaki, S., 2018, “Clinical Features of Otolith Organ-Specific Vestibular Dysfunction,” Clin. Neurophysiol., **129**(1), pp. 238–245.
[3] “Development of the Vestibular System and Balance Function: Differential Diagnosis in the Pediatric Population- ClinicalKey” [Online]. Available: https://www-clinicalkey-com.proxy.lib.umich.edu/#!/content/playContent/1-s2.0-S0030666511000028?returnurl=https:%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0030666511000028%3Fshowall%3Dtrue&referrer=https:%2F%2Fwww.scopus.com%2Frecord%2Fdisplay.uri%3Feid%3D2-s2.0-79953302617%26origin%3Dresultslist%26sort%3Dplf-f%26src%3Ds%26st1%3D%26st2%3D%26sid%3Da0ec26bd642fbd5aa049dc26715568df%26sot%3Db%26sdt%3Db%26sl%3D73%26s%3DTITLE-ABS-KEY%2B%2528%2522vestibular%2Bdisorders%2522%2BAND%2B%2522gait%2522%2BAND%2B%2522vertigo%2522%2BAND%2B%2522ear%2522%2529%26relpos%3D11%26citeCnt%3D25%26searchTerm%3D. [Accessed: 01-Mar-2021].
[4] Sienko, K. H., Whitney, S. L., Carender, W. J., and Wall, C., 2017, “The Role of Sensory Augmentation for People with Vestibular Deficits: Real-Time Balance Aid and/or Rehabilitation Device?,” J. Vestib. Res. Equilib. Orientat., **27**(1), pp. 63–76.
[5] Taborri, J., Palermo, E., Rossi, S., and Cappa, P., 2016, “Gait Partitioning Methods: A Systematic Review,” Sensors, **16**(1).
[6] “Implantable Electronic Medical Devices - 1st Edition” [Online]. Available: https://www.elsevier.com/books/implantable-electronic-medical-devices/fitzpatrick/978-0-12-416556-4. [Accessed: 01-Mar-2021].
[7] Castermans, T., Duvinage, M., Cheron, G., and Dutoit, T., 2013, “Towards Effective Non-Invasive Brain-Computer Interfaces Dedicated to Gait Rehabilitation Systems,” Brain Sci., **4**(1), pp. 1–48.
[8] Perry, J., c1992., *Gait Analysis :Normal and Pathological Function /*, Thorofare, N.J. :
[9] Anwary, A. R., Yu, H., Callaway, A., and Vassallo, M., 2021, “Validity and Consistency of Concurrent Extraction of Gait Features Using Inertial Measurement Units and Motion Capture System,” IEEE Sens. J., **21**(2), pp. 1625–1634.
[10] Rhea, C. K., and Kuznetsov, N. A., 2017, “Using Visual Stimuli to Enhance Gait Control,” J. Vestib. Res. Equilib. Orientat., **27**(1), pp. 7–16.
[11] Kim, S. C., Kim, J. Y., Lee, H. N., Lee, H. H., Kwon, J. H., Kim, N. beom, Kim, M. J., Hwang, J. H., and Han, G. C., 2014, “A Quantitative Analysis of Gait Patterns in Vestibular Neuritis Patients Using Gyroscope Sensor and a Continuous Walking Protocol,” J. NeuroEngineering Rehabil., **11**, p. 58.
[12] Nascimbeni, A., Gaffuri, A., Penno, A., and Tavoni, M., 2010, “Dual Task Interference during Gait in Patients with Unilateral Vestibular Disorders,” J. NeuroEngineering Rehabil., **7**(1), p. 47.
[13] Shea, C. H., Wulf, G., Whitacre, C. A., and Park, J.-H., 2001, “Surfing the Implicit Wave,” Q. J. Exp. Psychol. Sect. A, **54**(3), pp. 841–862.
[14] Xu, J., Bao, T., Lee, U. H., Kinnaird, C., Carender, W., Huang, Y., Sienko, K. H., and Shull, P. B., 2017, “Configurable, Wearable Sensing and Vibrotactile Feedback System for Real-Time Postural Balance and Gait Training: Proof-of-Concept,” J. NeuroEngineering Rehabil., **14**(1).
[15] “Anatomical Terms” [Online]. Available: https://cnx.org/contents/Gko70fNo%401/Anatomical-Terms. [Accessed: 09-Feb-2021].
[16] Biesmans, S., Markopoulos, P., and Link to external site, this link will open in a new window, 2020, “Design and Evaluation of SONIS, a Wearable Biofeedback System for Gait Retraining,” Multimodal Technol. Interact., **4**(3), p. 60.
[17] Kingma, H., Felipe, L., Gerards, M.-C., Gerits, P., Guinand, N., Perez-Fornos, A., Demkin, V., and van de Berg, R., 2019, “Vibrotactile Feedback Improves Balance and Mobility in Patients with Severe Bilateral Vestibular Loss,” J. Neurol., **266**, pp. 19–26.

[18] Ma, C. Z.-H., Wong, D. W.-C., Lam, W. K., Wan, A. H.-P., and Lee, W. C.-C., 2016, “Balance Improvement Effects of Biofeedback Systems with State-of-the-Art Wearable Sensors: A Systematic Review,” Sens. Switz., **16**(4).
[19] Janssen, M., Pas, R., Aarts, J., Janssen-Potten, Y., Vles, H., Nabuurs, C., Lummel, R. van, Stokroos, R., and Kingma, H., 2012, “Clinical Observational Gait Analysis to Evaluate Improvement of Balance during Gait with Vibrotactile Biofeedback,” Physiother. Res. Int., **17**(1), pp. 4–11.
[20] Kal, E., Prosée, R., Winters, M., and van der Kamp, J., 2018, “Does Implicit Motor Learning Lead to Greater Automatization of Motor Skills Compared to Explicit Motor Learning? A Systematic Review,” PloS One, **13**(9), p. e0203591.
[21] Schniepp, R., Möhwald, K., and Wuehr, M., 2019, “Clinical and Automated Gait Analysis in Patients with Vestibular, Cerebellar, and Functional Gait Disorders: Perspectives and Limitations,” J. Neurol., **266**(1), pp. 118–122.
[22] Basta, D., Rossi-Izquierdo, M., Soto-Varela, A., Greters, M. E., Bittar, R. S., Steinhagen-Thiessen, E., Eckardt, R., Harada, T., Goto, F., Ogawa, K., and Ernst, A., 2011, “Efficacy of a Vibrotactile Neurofeedback Training in Stance and Gait Conditions for the Treatment of Balance Deficits: A Double-Blind, Placebo-Controlled Multicenter Study,” Otol. Neurotol., **32**(9), pp. 1492–1499.
[23] “SwayStar ™ Balance International Innovations GmbH::Home” [Online]. Available: https://www.b2i.info/web/index.htm?/manuals/webhelp/2.2_SwayStar_LITERATURE_ON_TRUNK_SWAY_DURING_STANCE_ANDGAIT.htm. [Accessed: 09-Feb-2021].
[24] Rust, H., Lutz, N., Zumbrunnen, V., Imhof, M., Yaldizli, O., Haller, V., and Allum, J., 2020, “Benefits of Short-Term Training with Vibrotactile Biofeedback of Trunk Sway on Balance Control in Multiple Sclerosis,” Phys. Med. Rehabil. Res., **5**.
[25] Ma, C. Z.-H., Zheng, Y.-P., and Lee, W. C.-C., 2018, “Changes in Gait and Plantar Foot Loading upon Using Vibrotactile Wearable Biofeedback System in Patients with Stroke,” Top. Stroke Rehabil., **25**(1), pp. 20–27.
[26] McKinney, Z., Heberer, K., Nowroozi, B. N., Greenberg, M., Fowler, E., and Grundfest, W., 2014, “Pilot Evaluation of Wearable Tactile Biofeedback System for Gait Rehabilitation in Peripheral Neuropathy,” pp. 135–140.
[27] Mazilu, S., Blanke, U., Hardegger, M., Troster, G., Gazit, E., Dorfman, M., and Hausdorff, J. M., 2014, “GaitAssist: A Wearable Assistant for Gait Training and Rehabilitation in Parkinson’s Disease,” pp. 135–137.
[28] Xu, W., Huang, M.-C., Amini, N., Liu, J. J., Electrical, L. H., and Sarrafzadeh, M., 2012, “Smart Insole: A Wearable System for Gait Analysis.”
[29] Redd, C. B., and Bamberg, S. J. M., 2012, “A Wireless Sensory Feedback Device for Real-Time Gait Feedback and Training,” IEEEASME Trans. Mechatron., **17**(3), pp. 425–433.
[30] Gavriel Salvendy, 2012, *Handbook of Human Factors and Ergonomics*, Wiley, Hoboken.
[31] Murray, M., Drought, A., and Kory, R., 1964, “Walking Patterns of Normal Men,” J. Bone Jt. Surg. - Am. Vol., **46**(2), pp. 335–360.
[32] Jabri, S., DiCesare, C., and Ferris, J., 2021, “Interview #2.”
[33] Cimolin, V., Galli, M., Albertini, G., Crivellini, M., Romkes, J., and Brunner, R., 2012, “Quantitative Analysis of Upper Limbs during Gait: A Marker Set Protocol,” J. Appl. Biomater. Funct. Mater., **10**(1), pp. 49–55.
[34] Abass, S., Ghazi, M., and Alalsaidissa, J., 2017, “□The Effects of Body Mass Index BMI on Human Gait Analysis.”
[35] Chen, S., Brantley, J., Kim, T., Ridenour, S., and Lach, J., 2013, “Characterizing and Minimizing Sources of Error in Inertial Body Sensor Networks,” Int. J. Auton. Adapt. Commun. Syst., **6**, pp. 253–271.
[36] Moyer, B. C., Branum, A. M., Paulose-Ram, R., and Akinbami, L. J., 2021, *Anthropometric Reference Data for Children and Adults: United States, 2015–2018*, 46, National Center for Health Statistics.
[37] Young, J., 1993, *Head and Face Anthropometry of Adult U.S. Civilians*, AD-A268 661, Civil

Aeromedica, Institute Federal Aviation Administration.
[38] Margaret A. McDowell, Fryar, C. D., Ogden, C. L., and Flegal, K. M., 2008, *Anthropometric Reference Data for Children and Adults: United States, 2003–2006*, 10, U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES.
[39] Garrett, J. W., 1971, "The Adult Human Hand: Some Anthropometric and Biomechanical Considerations," Hum. Factors, **13**(2), pp. 117–131.
[40] Van Erp, J. B. F., 2005, "Vibrotactile Spatial Acuity on the Torso: Effects of Location and Timing Parameters," pp. 80–85.
[41] Sienko, K., Jabri, S., and DiCesare, C., 2021, "Interview #1."
[42] Jabri, S., 2021, "Interview #4."
[43] Zhou, L., Fischer, E., Tunca, C., Brahms, C. M., Ersoy, C., Granacher, U., and Arnrich, B., 2020, "How We Found Our IMU: Guidelines to IMU Selection and a Comparison of Seven IMUs for Pervasive Healthcare Applications," Sensors, **20**(15).
[44] Zhao, H., Qiu, S., Wang, Z., Yang, N., Li, J., and Wang, J., 2019, "Applications of MEMS Gyroscope for Human Gait Analysis," Gyroscopes - Princ. Appl.
[45] Sienko, K., and Jabri, S., 2021, "Interview #3."
[46] Information, N. C. for B., Pike, U. S. N. L. of M. 8600 R., MD, B., and Usa, 20894, 2017, *Hearing Loss and Deafness: Normal Hearing and Impaired Hearing*, Institute for Quality and Efficiency in Health Care (IQWiG).
[47] 2021, *Xsens/Xsens_dot_server*, Xsens.
[48] Solarbotics, "VPM2 Datasheet" [Online]. Available: https://www.robotshop.com/media/files/pdf/datasheet-vpm2.pdf. [Accessed: 21-Mar-2021].
[49] Jabri, S., and DiCesare, C., 2021, "Interview #5."
[50] "Voltage and DC Motor Speed - Motion Control Tips" [Online]. Available: https://www.motioncontroltips.com/faq-whats-relationship-voltage-dc-motor-output-speed/. [Accessed: 26-Apr-2021].
[51] Kavanagh, J. J., Barrett, R. S., and Morrison, S., 2004, "Upper Body Accelerations during Walking in Healthy Young and Elderly Men," Gait Posture, **20**(3), pp. 291–298.
[52] Sienko, K. H., Seidler, R. D., Carender, W. J., Goodworth, A. D., Whitney, S. L., and Peterka, R. J., 2018, "Potential Mechanisms of Sensory Augmentation Systems on Human Balance Control," Front. Neurol., **9**, p. 944.
[53] Goebel, J. A., Sinks, B. C., Parker Jr., B. E., Richardson, N. T., Olowin, A. B., and Cholewiak, R. W., 2009, "Effectiveness of Head-Mounted Vibrotactile Stimulation in Subjects with Bilateral Vestibular Loss: A Phase 1 Clinical Trial," Otol. Neurotol., **30**(2), pp. 210–216.
[54] Ma, C. Z.-H., and Lee, W. C.-C., 2017, "A Wearable Vibrotactile Biofeedback System Improves Balance Control of Healthy Young Adults Following Perturbations from Quiet Stance," Hum. Mov. Sci., **55**, pp. 54–60.
[55] Sienko, K. H., Balkwill, M. D., E. Oddsson, L. I., and Wall, C., 2008, "Effects of Multi-Directional Vibrotactile Feedback on Vestibular-Deficient Postural Performance during Continuous Multi-Directional Support Surface Perturbations," J. Vestib. Res. Equilib. Orientat., **18**(5/6), pp. 273–285.
[56] Ziaie, B., Kim, A., Kim, J., and Rietdyk, S., 2017, "United States Patent: 9801568 - Gait Pattern Analysis for Predicting Falls."
[57] Silk, J. E., 2010, "United States Patent: 7648441 - Self-Contained Real-Time Gait Therapy Device."
[58] Allum, J. H., and CH, 1999, "United States Patent: 5919149 - Method and Apparatus for Angular Position and Velocity Based Determination of Body Sway for the Diagnosis and Rehabilitation of Balance and Gait Disorders."

Appendix A: Benchmarking of Designs and Subject Feedback

A1. Commercially Available Wearable Biofeedback Devices for Static Balance and Gait Analysis

A number of wearable devices are commercially available that are used to track static balance and gait and/or provide biofeedback. Some of these devices are shown in Table A.1 and are discussed in further detail below.

Table A.1. Commercially available wearable devices for static and dynamic balance with biofeedback.

Source	Sensor Type	Number of Sensors	Sensor Location	Feedback Type	Tactor Location	Number of Tactors	Attachment Type
Vertiguard [22]	gyroscope	---	waist	Vibrotactile	Front, back, left, right sides around waist	4	belt
SwayStar [23]	gyroscope	2	waist at level of lumbar spine	uses Balance Freedom			belt
Balance Freedom [24]	uses SwayStar			Audio; vibrotactile; visual	headband	8	----

I. Vertiguard [22] is a commercially available training product that tracks trunk sway during static and dynamic activities. The product consists of four vibrotactors and a main unit connected on a belt (Figure A1.1). The vibrotactors can slide around on the belt into the four locations: front, back, left, and right side of the waist. The main unit includes a sensor that measures body pitch and roll with gyroscopes. Vibrotactile feedback was applied to the location of sway, with the vibrations increasing with body sway amplitude for about 1 second.

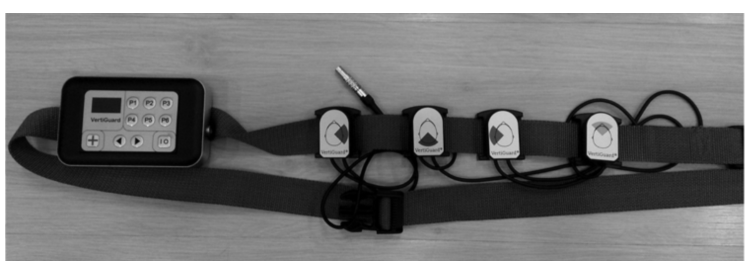


Figure A1.1 [22]**:** Vertiguard consists of a main unit (houses a sensor) and four vibrotactors.

II. SwayStar™ [23] (Figure A1.2) is a device worn around the waist (at level of lumbar spine) that consists of two gyroscopes [24] and monitors angular deviations and angular velocities of the trunk during activities including standing, walking, stairs, slopes, sit to stand, and reaching. Putting the sensor on the trunk (near the center of mass) results in measurements that can quantify a fall because it is independent of linear speed and trunk movement directly relates to balance instability. SwayStar^{TM} does not provide immediate feedback and is only used as a device to measure trunk sway.

Figure A1.2 [23]**:** SwayStar^{TM} is worn around the waist at the level of the lumbar spine and is held in position with a belt.

III. Balance Freedom^{TM} [24] (Figure A1.3) is an extension to the SwayStar^{TM} that combines vibrotactile, auditory, and visual feedback. SwayStar^{TM} is used to measure trunk sway. Balance Freedom^{TM} consists of eight vibrotactors evenly spaced around a headband, with the tactor in the direction of sway being activated [24]. Vibrotactile and auditory feedback have a lower activation threshold for trunk sway compared to the threshold for visual feedback. The device is placed on the head, resulting in faster cognitive processing of the vibrotactile feedback. The auditory feedback is provided through bone-conduction acoustic transducers, limiting the effect of interference on hearing natural stimuli.

Figure A1.3 [24]**:** Balance Freedom™ is an extension of SwayStar™ providing multimodal feedback.

A2. Wearable Static Balance Devices Providing Vibrotactile Biofeedback used in Research

Three wearable devices used in research to track static balance and provide vibrotactile feedback are shown in Table A.2 and discussed in detail below.

Table A.2. Wearable static balance devices used in research providing vibrotactile feedback.

Source	Sensor Type	Number of Sensors	Sensor Location	Tactor Location	Number of Tactors	Attachment Type
Goebel et al. [53]	6-DOF IMU	1	Back of head	Head	4	elastic cloth headband
Ma and Lee [54]	Plantar force sensor	4	Bottom of foot (2 per foot)	sternum, back, left/right arm	4	adhesive tapes (sensors)
Sienko et al. [55]	2-DOF IMU	1	Lower back	Torso	3x16, 3x8, 3x4 arrays	----

I. Goebel et al. [53] used a 6-DOF IMU consisting of accelerometers and gyroscopes to track pitch/roll of head and head orientation. The sensor was located at the back of the subject's head. There were four vibrotactors located on the head, 90° apart from each other (Figure A2.1). Feedback was provided at up to two locations at once. The sensors and vibrotactors are held in place with an elastic cloth headband. Other hardware was stored on the back of the subject. Two types of vibrotactile feedback was given: (1) feedback indicating direction and magnitude of head tilt (move away from feedback) and (2) feedback indicating direction of vertical relative to gravity and magnitude relative to current head position (move towards feedback). The second type of feedback was found to be ineffective at improving balance.

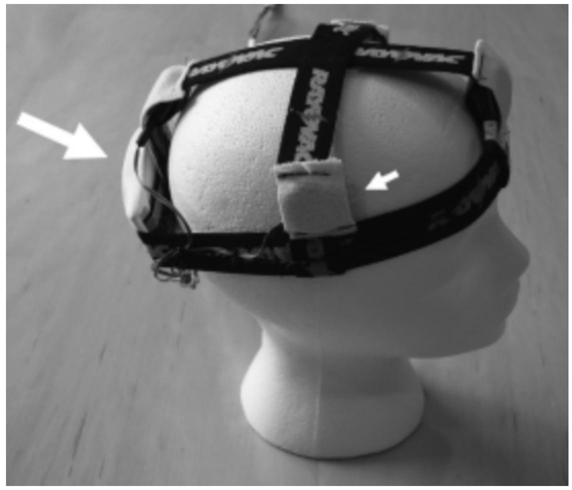


Figure A2.1 [53]**:** The large arrow points to the sensor location and the small arrow points to one of the vibortactors.

II. Ma and Lee [54] designed a wearable device that provides immediate vibrotactile feedback based on plantar force measurements. Plantar force sensors were used, as opposed to IMUs attached to the trunk, to reduce size and mass. Four plantar force sensors (two per foot) were taped to an insole under the first metatarsal head and heel of both feet. If the forces exceed a threshold, vibrotactile feedback is provided to four possible tactors, located at the sternum, the back, and the left and right arms. The tactor that is activated depends on the direction of increased body sway.
III. Sienko et al. [55] used a 2-DOF IMU (gyroscopes and accelerometers) to monitor tilt angle as the floor was perturbed. The sensor was located on the subject's lower back. The subject wore a belt around their torso that consisted of tactor arrangements of 3x16, 3x8, and 3x4 tactor arrays. The activated tactor row provided feedback on the tilt magnitude, and the activated tactor column provided feedback on the tilt direction. Only one tactor was activated at a time.

A3. Wearable Gait Analysis Devices Providing Vibrotactile Biofeedback used in Research

There are a number of wearable devices used in research that track various gait parameters and provide vibrotactile feedback. Some of the devices are shown in Table A.3 and discussed more in detail below.

Table A.3. Wearable gait analysis devices used in research providing vibrotactile feedback.

Source	Sensor Type	Number of Sensors	Sensor Location	Feedback Type	Tactor Location	Number of Tactors	Attachment Type
Janssen et al. [19]	3-DOF IMU	1	head or trunk	Vibrotactile	Waist	12	elastic belt band with Velcro
Kingma et al. [17]	6-DOF IMU	1	back of belt on waist	Vibrotactile	waist	12	----
Xu et al. [14]	9-DOF IMU	up to 8	left and right side of torso or shank (depending on measurement)	Vibrotactile	left and right side of torso or shank (depending on measurement)	up to 8	----
Ma, Zheng, Lee [25]	Plantar force sensor	2	first and fifth metatarsal	Vibrotactile	wrist of affected side	1	adhesive tape (sensors); elastic band (tactor)
McKinney et al. [26]	Plantar force sensors	8	hallux, first/fifth metatarsal, heel (4 per foot)	Vibrotactile	thigh	4x3 array	neoprene thigh cuffs

I. Janssen et al. [19] used a device consisting of a 3-DOF accelerometer placed on the head or trunk to monitor head or body tilt, respectively. Twelve actuators (vibrotactors) are equally spaced around the waist (Figure A3.1) and held in place with an elastic belt and Velcro. A microprocessor is used to activate the actuators. The battery pack powers the processor, actuators, and sensors for 72 hours, so the device can be used for days without needing to be charged. The magnitude (angle from vertical) and direction of tilt determines which actuator that is activated. The actuator in the direction of tilt is activated, and as the angle of tilt is increased, additional actuators in the direction of tilt are activated until the subject adjusts and enters the no-feedback zone.

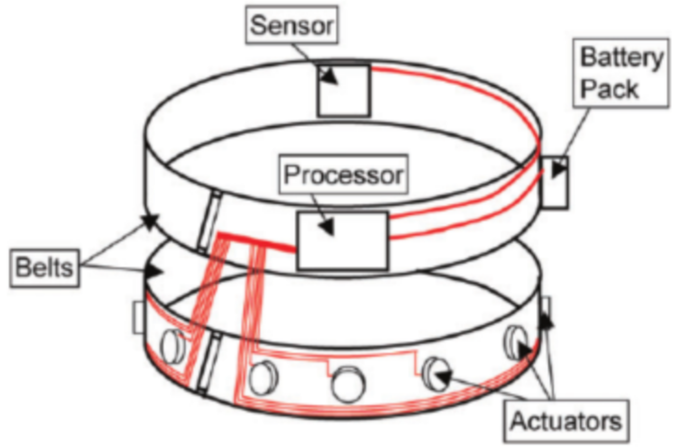


Figure A3.1 [19]**:** A schematic of the device used in the situation where the sensor is placed on the trunk.

II. Kingma et al. [17] designed a device to be used long-term, as opposed to rehabilitation programs, for static and dynamic activities. A 6-DOF IMU, located at the back of the belt, (accelerometer and gyroscope) measures tilt relative to the gravity vector. The feedback display consists of 12 tactors evenly spaced on a belt around the waist (Figure A3.2). Vibrotactile feedback is applied to the tactor in the direction of tilt. A vibration is applied at 300 Hz for 150 ms at a rate of 4 Hz. The device has a battery life of at least 16 hours of continuous use.

Figure A3.2 [17]**:** The device designed by Kingma et al. to be worn long-term as a belt to provide vibrotactile feedback on tilt angle.

III. Xu et al. [14] designed a device that consisted of eight nodes that could be used for sensing and vibrotactile feedback. Each node has a 9-DOF IMU for sensing. A main unit, clamped to a waistband, receives sensor data from the nodes and sends feedback signals back to the nodes, making this a device that is fully portable. To measure trunk tilt, a sensor was placed at the lower spine, and vibrotactile feedback was provided to the left and right sides of the torso. Feedback was provided to move away from the vibration. The device was also used to measure foot progression angle (FPA). To do measure FPA, a sensor was placed on the dorsal side of the foot, and vibrotactile feedback was provided to the medial and lateral sides of the shank.

IV. Ma, Zheng, and Lee [25] designed a device that measured plantar forces at the medial and lateral forefeet. Two plantar force sensors were taped to an insole at the first and fifth metatarsals. One vibrotactor was attached to a wrist with an elastic strap. The device was used with hemiplegic stroke patients so only one side of the body was observed. The vibrotactor was activated when the measured force at the first metatarsal was lower than 50% of the measured force at the fifth metatarsal.

V. McKinney et al. [26] designed a device consisting of eight force sensors (four per foot) attached to an insole on the hallux, first/fifth metatarsal, and heel (centers of pressure during gait). Feedback is provided via two neoprene thigh cuffs with a 4x3 array of silicone balloon elements. The four columns provided feedback to the anterior, posterior, medial, and lateral areas of thigh based on data from the toe, heel, and medial/lateral areas of the foot, respectively. This resulted in a one-to-one mapping of force to feedback. The feedback row that was activated indicated the force sensor magnitude.

A4. Wearable Gait Biofeedback (Visual, Audio, Multimodal) Devices used in Research

In addition to wearable devices used to track gait that provide vibrotactile feedback, there is research being done to provide biofeedback in other modalities including visual, audio, or a combination. Some of these devices are shown in Table A.4 and discussed in more detail below.

Table A.4. Wearable gait analysis devices used in research providing auditory, visual, or multimodal feedback.

Source	Sensor Type	Number of Sensors	Sensor Location	Feedback Type
Mazilu et al. [27]	9-DOF IMU	2	ankles	Audio (non-speech), (phone)
Xu et al. [28]	Plantar force sensor and 9-DOF IMU	48 pressure sensors; 1 IMU	bottom of foot	Visual (phone GUI)
Redd and Bamberg [29]	Force sensitive resistor	4	bottom of foot (2 per foot)	Visual; Audio; Vibrate; (phone)
Biesmans and Markopoulos [16]	Textile pressure sensor	10	bottom of foot (5 per foot)	Audio (non-speech); Visual (phone)

I. Mazilu et al. [27] developed GaitAssist, which detects gait freezing in Parkinson's Disease patients. Two 9-DOF IMUs (accelerometer, gyroscope, magnetometer) are attached to the subject's ankles and monitor motion to detect gait freezing. When gait freezing is identified, rhythmic audio feedback is provided through a phone for up to 20 seconds as the subject tries to walk in sync with the audio feedback.

II. Xu et al. [28] developed Smart Insole consisting of 48 pressure sensors, located under the foot to obtain a pressure map, and a 3-DOF accelerometer, gyroscope, and compass, all located under the heel. The device has a graphical user interface (GUI) that displays data about the pressure, roll/pitch/yaw angular velocity, and step number. There are eight gait features that can be analyzed: pressure distribution, number of steps, cadence (steps/min), step time, swing time (foot lift to landing time), stance time, stance to swing ratio, and dual limb support time. Visual feedback is displayed to the user interface on a smartphone.

III. Redd and Bamberg [29] used two force sensitive resistors placed at the forefoot and the hindfoot to measure plantar forces. Using only two sensors allowed for increased sampling rate and preserves the ability to calculate gait abnormalities (calculated with ratio of stance time for each foot). This design has multimodal feedback consisting of auditory, visual and vibrotactile feedback delivered from a smartphone. The subject can select one of the feedback modes, and feedback is given when the ratio of stance time for each foot falls outside an acceptable range.

IV. Biesmans and Markopoulos [16] designed SONIS, a smart sock with five textile pressure sensors that detect unwinding of the foot and heel-to-toe timing. The sensors are located under the anterior and posterior heel, the first/fourth metatarsal, and the big toe. Visual feedback is provided to a smart phone showing pressure maps of the feet. There is also an option for auditory (voices) feedback based on a selected gait parameter.

A5. Various patents related to gait tracking and biofeedback research

I. Kim Albert designed a device consisting of a belt attached with a camera. Markers are placed on the individual's feet or legs, and the camera is meant to watch and track the gait of an individual based on the movement of these markers [56].

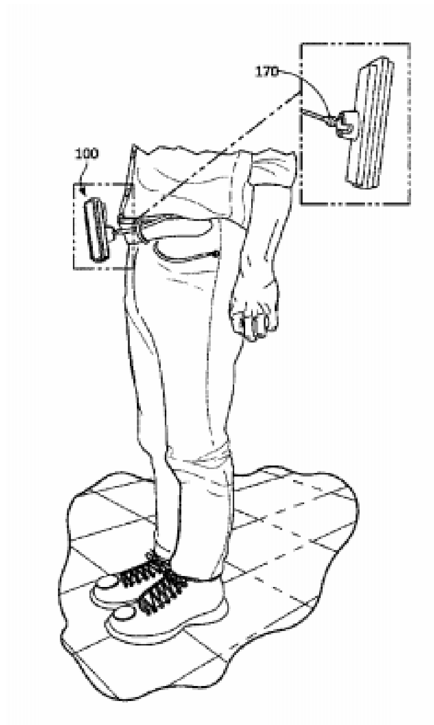


Figure A5.1 [56]**:** The device designed by Albert to track and analyze an individual's gait based on their feet movement (tracked by a camera attached to their waist).

II. Jeffrey Silk designed a device consisting of a gait sensor, actuator, output speaker, and battery receptacle enclosed in a belt clip. The device was designed to track step duration, step impact force, and step form data based on the sensors within and provide auditory feedback based on any perceived changes in the individual's usual gait. The device was created with the pure intention of providing a therapy device that was mobile and could give real-time feedback to help prevent potential falls of an individual [57].

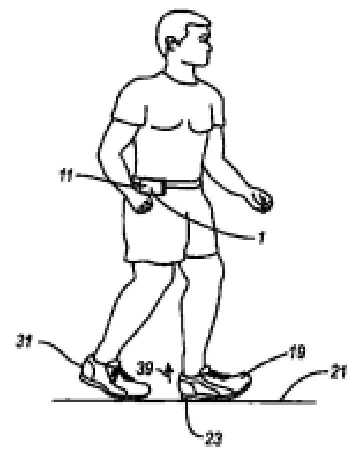


Figure A5.2 [57]**:** The device designed by Silk to analyze an individual's gait and provide auditory feedback all through a simple belt attachment.

III. John Allum designed a device to track the body sway of an individual and provide feedback based on any sensed abnormalities in the sway of the body. Body sway was measured using angular velocity transducers placed in a harness attached around a subject's chest. Feedback could be registered in many ways: in an auditory sense through a speaker worn on the chest harness, in a vibrotactile sense through tactual actuators also placed on the harness, or in a visual sense through a mounted pair of eyewear [58].

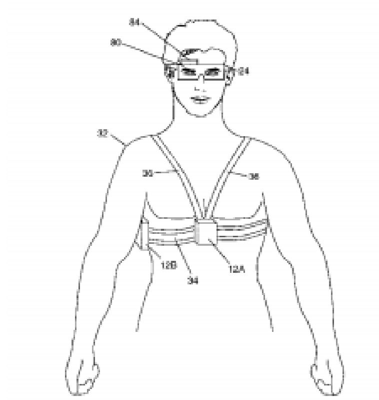


Figure A5.3 [58]**:** The device designed by Allum to analyze an individual's body sway and give feedback in multiple possible ways.

Appendix B: Scripts using in Engineering Analysis

B.1. Two tactor activation in Python

```
"""
   Kristina Nunez <krnunez@umich.edu>
   3/17/2021

   Activate 2 tactors on a Raspberry Pi.
   Input: N/A
   Output: Tactor activation in GPIO2 and GPIO3 on Raspberry Pi.
"""

import RPi.GPIO as GPIO
import time

# configure the pin numbering to GPIO board
GPIO.setmode(GPIO.BOARD)

# set up pin 3 and 5 as outputs
GPIO.setup(3, GPIO.OUT)
GPIO.setup(5, GPIO.OUT)

"""
   0-1 seconds: pin 3 on
   1-2 seconds: pin 3, 5 on
   2-3 seconds: pin 5 on
   3-4 seconds: no pins on
"""
while true:
   GPIO.output(3, GPIO.HIGH)
   time.sleep(1)
   GPIO.output(5, GPIO.HIGH)
   time.sleep(1)
   GPIO.output(3, GPIO.LOW)
   time.sleep(1)
   GPIO.output(5, GPIO.LOW)
   time.sleep(1)

GPIO.cleanup()
```

B.2. Two tactor activation with IMU data in Python

```python
"""
   Kristina Nunez <krnunez@umich.edu>
   3/19/2021

   Activate 2 tactors on a Raspberry Pi based on IMU data.
   Input: IMU data in a csv file called 'SampleData.csv'.
   Output: Tactor activation in GPIO2 and GPIO3 on Raspberry Pi.
"""

import csv
import time
import RPi.GPIO as GPIO

IMU_data = {}

# Read in data file
with open('SampleData.csv') as csvfile:
   reader = csv.reader(csvfile)

   # Skip header lines
   for i in range(6):
       next(reader)

   # Process all lines with IMU data
   for row in reader:
       timestamp = row[0]

       # Store data in dict by timestamp
       IMU_data[timestamp] = {
           "euler_x": float(row[2]),
           "euler_y": float(row[3]),
           "euler_z": float(row[4]),
           "acc_x": float(row[5]),
           "acc_y": float(row[6]),
           "acc_z": float(row[7]),
       }

sample_freq = 60

# Update parameter and threshold based on need
parameter_1 = "euler_z"
threshold_1 = 27

parameter_2 = "euler_x"
threshold_2 = 0.7

# Configure the pin numbering to GPIO board
GPIO.setmode(GPIO.BOARD)

# Set up pin 3 and pin 5 as outputs
GPIO.setup(3, GPIO.OUT)
GPIO.setup(5, GPIO.OUT)
```

```
print("Trial Start")

# Iterate through data in time order
for t, data in list(IMU_data.items()):
   # if IMU parameter_1 is out of range, turn tactor on
   if data[parameter_1] > threshold_1:
       GPIO.output(3, GPIO.HIGH)
   # if IMU parameter is in range, turn tactor off
   else:
       GPIO.output(3, GPIO.LOW)

   #if IMU parameter_2 is out of range, turn tactor on
   if data[parameter_2] > threshold_2:
       GPIO.output(5, GPIO.HIGH)
   # if IMU parameter is in range, turn tactor off
   else:
       GPIO.output(5, GPIO.LOW)

   # delay of time between samples to simulate real time data collection and tactor
activation
   time.sleep(1/sample_freq)

# Turn off all tactors at end
GPIO.output(3, GPIO.LOW)
GPIO.output(5, GPIO.LOW)
GPIO.cleanup()

print("Trial End")
```

B.3. Two Tactor Activation in C++

```
/* Kristina Nunez <krnunez@umich.edu>
   3/18/2021
*/

#include <wiringPi.h>
#include <dos.h>

using namespace std;

int main(){
   // Initializes wiringPi using the Broadcom GPIO pin numbers
   wiringPiSetupGpio();

   // initializes pins to use as output
   pinMode(2, OUTPUT);
   pinMode(3, OUTPUT);

   /*
       0-1 seconds: pin 3 on
       1-2 seconds: pin 3, 5 on
       2-3 seconds: pin 5 on
       3-4 seconds: no pins on
   */
   while(true){
       digitalWrite(2, HIGH);
       delay(1000);
       digitalWrite(3, HIGH);
       delay(1000);
       digitalWrite(2, HIGH);
       delay(1000);
       digitalWrite(3, HIGH);
       delay(1000);
   }

   return 0;
}
```

Appendix C: Researcher Interface Video Demo

The provided link shows how the full scale researcher interface will appear to the researchers. Note that in this video there are no IMUs connected. The video shows the entire layout and how the researcher can interact with each input. The video also shows how there are files that downloaded when the researcher clicks certain buttons for feedback that the researcher has set the trail settings correctly.

https://drive.google.com/file/d/1mZ7GwfUks9m1D7S5Fpp368QVfcaSSq7M/view?usp=sharing

Appendix D: Researcher Interface README

The provided link is a link to a PDF of the researcher interface README.md documentation provided to our stakeholders with our final design.
https://drive.google.com/file/d/1JRjUAW8iT1nAtMhyckEIgTVkwyQyWVfo/view?usp=sharing

Appendix E: Bill of Materials

See Figure E.1 for a full list of the components we used in our project design.

Part No.	Part Title	Source/Brand	Quantity	Price
1	Coin Vibe Motor	MBientlab	10	$50.00
2	VPM 2 Vibrating Disk	Robot Shop	10	$35.00
3	Arduino Uno R3	Robot Shop	1	$21.99
4	8GB Raspberry Pi 4	Canakit	1	$119.99
5	32GB Samsung EVO+ Micro SD Card (Class 10) Pre-loaded with NOOBS		1	
6	USB MicroSD Card Reader		1	
7	Raspberry Pi 4 Case with Integrated Fan Mount		1	
8	Raspberry Pi 4 Power Supply		1	
9	Heat Sinks (3 different ones)		1	
10	Micro HDMI to HDMI Cable - 6 foot		1	
11	USB-C PiSwitch (On/Off Power Switch for Raspberry Pi 4)		1	
12	Breadboard	ELEGOO	1	
13	USB Battery Pack for Raspberry Pi - 10000mAh - 2 x 5V outputs	Adafruit	1	$54.55
14	Bipolar (BJT) Transistor Array 8 NPN Darlington 50V 500mA - 2.25W Through Hole 18-DIP	Digikey	4	$12.63
15	Tenergy 2 Pack NiMH Receiver RX Battery with Hitec Connectors 4.8V 2000mAh High Capacity Rechargeable Battery Pack	Tenergy		$16.99
16	VPM2 Vibrating Disk Motor	Solarbotics	24	$94.80
17	Joyzy Reflective Bands, Ankle Band 11 Inch, with Small Pouch Mesh Pocket	Joyzy	3	$32.97
18	CISONE 8 Inch Wide Black Heavy Stretch High Elasticity Knit Elastic Band 2 Yards	CISONE	1	$14.99
19	8 Inch Wide Black Heavy Stretch High Elasticity Knit Elastic Band 1 Yard	CISONE	1	$9.99
20	TYONMUJO Unisex Adult Knit Beanie for Men Women Warm Snug Hat Cap	TYONMUJO	1	$6.93
21	Sew on Hook and Loop Style 4 Inch Non-Adhesive Back Nylon Strips Fabric Fastener Non-Adhesive Interlocking Tape Black,3 Yard	MYUREN	1	$13.95
22	Male tactor housing	3D Printing	24	-
23	Female tactor housing	3D Printing	28	-
24	Tactor electronics casing (walls)	3D Printing	1	-
25	Tactor electronics casing (base)	3D Printing	1	-
26	Half-buckle	3D Printing	2	-
27	Raspberry Pi 4 base	3D Printing	1	-
28	30 Feet Spool, 22 gauge Jumper wire	X50 Lab	1	-
29	Xsens DOT IMUs	Xsens DOT	5	$620.00

Figure E.1: Bill of materials for our project.

Appendix F: Supplemental Information

F.1. Engineering Standards

Throughout our project, we did not use any engineering standards. We looked into standards for a number of design aspects, including applying vibrations to skin, providing auditory cues, and the safety of our wearable design aspects, but we did not have success finding any engineering standards that applied to our project. Since this is a research tool, there will need to be safety standards that are met prior to the design being research ready. We looked into the Michigan Medicine Clinical Engineering Research Review Unit (formerly BEU) to try to find safety standards that would need to be met before our design could be used in a research setting, but we were unable to find anything publicly available. While we did not use any engineering standards in the design of our device, we recognize that there are safety standards that will need to be met for future design iterations as the device develops from the proof of concept to a research ready tool.

F.2. Engineering Inclusivity

For our project, we had to keep our focus on making a wearable solution that would address the needs of our stakeholders - researchers - but also address the needs of their research subjects. To do both of these things, we first extensively researched constraints regarding our stakeholders. The most important things regarding stakeholder needs are maintenance of the wearable solution and customizable programming for instructions sent to the wearable device. To ensure we met these needs, we have conducted several interviews with our stakeholders to understand the bounds in which we can design within. For maintenance, the stakeholders informed us that ensuring parts are easily removable for when the wearable device has to be washed and ensuring removing/attaching solution components is not complex would be good aspects of the design. From these requests, we incorporated a male-female tactor housing assembly to allow for the easy attachment and removal of tactor components from the wearable device by nearly anyone with prying capabilities. Our Raspberry Pi 4 component has a base that is very similar to that of the tactor housing assembly for easy attachment and removal. We've also fabricated elastic pockets onto the wearable device for housing the power supplies of all electronics on the device. With these pockets, removing and installing the power supplies can be done with ease by sliding them on or off.

To reduce complexity in removing/attaching solution components, we have ensured to place great focus on solution components that stakeholders will be accessing more frequently than others. These solution components are tactors, the tactor electronics box, the tactor power supply, the Raspberry Pi 4 power supply, and IMUs. The tactors are simplified for attachment/removal as explained in the paragraph above, and the same can be said for the power supplies. The tactor electronics box has a lot of wires extending from the Raspberry Pi 4 input pins and tactors that need to have precise placement to ensure correct operating scenarios, so extensive labeling has been done to guide anyone who has to do maintenance on the device. Documentation has also been made to guide individuals through disassembling and reassembling the tactor electronics box components. With labeling in place, anyone can pick up the wearable device and conduct maintenance on it.

After accommodating for the needs and experience of our stakeholders, we then focused our attention on the needs of the testing subjects that will be wearing the solution. This meant accommodating for individuals with allergies to certain materials and ensuring that our device can fit a large variety of wearers. Our wearable device prototype utilizes the following materials: PETG plastic, cotton, and latex. Latex is a material that individuals are more prone to be allergic to, but this was a necessary material for the operation of this device, for it provides the flexibility necessary for accommodating any stretching of the straps. We include a disclaimer on the physical prototype to ensure wearers know that latex is used in the strap. The PETG and cotton do not cause any allergic reactions as far as our research tells us. Our device accommodates a variety of user head, waist, calf, and wrist circumferences based on 95th and 5th body measurement percentile data.

One thing our team wishes we could have done is speak with previous testing subjects to gather feedback on the research devices they have worn in the past related to the research that our stakeholders are conducting. Doing this would have informed our material choices and component designs in ways that would potentially benefit the testing subjects and stakeholders substantially. We recommend gathering this form of feedback from testing subjects that wear the current prototype of our design solution to inform iterative prototype designs.

F.3. Environmental Context

Our design features reusable material such as elastic bands and commercially available wrist and ankle bands. Also, the attachment methods for tactors and electrical components, which are 3D printed parts, are semi-permanent and reusable. This helps reduce waste compared to relying on disposable materials such as tape, clip, or other one-time use plastic materials. Our device does make progress towards an unmet social challenge of helping those with balance disorders. As a research tool, our device will allow researchers to better study the effects of balance disorders, particularly vestibular disorders, and human gait. Our device is not intended for mass production which indicates that our design does not cause any substantial negative environmental impact, such as factory pollution and waste. In the process of assembling the first prototype, we have noticed some downsides of the design. Potential waste can occur while treating the 3D printed parts when the parts fail and need to be replaced. Moreover, another source of waste is the electrical components, especially the wires which are susceptible to breaking. We recommend finding alternatives for fragile 3D printed parts and wires, and replace them for a longer life cycle. Furthermore, we recommend using recyclable plastic for tactor attachment methods for a more environmentally friendly device.

F.4. Social Context

To determine the social context/impact of our project, we sought to answer three critical questions: 1. Is the system likely to be adopted and self sustaining in the market? 2. Is the system so likely to succeed economically that planetary or social systems will be worse off? 3. Is the sustainable technology resilient to disruptions in business as usual?

1. Is the system likely to be adopted and self sustaining in the market?

To answer this question, we looked into the target demographic for our device. At this moment in time, our project has been designed for research purposes only, where our stakeholders will be using it to determine how vibrotactile feedback impacts gait performance for people with vestibular disorders. Because our project will be mostly used in the lab, we do not expect it to enter the market. However, should our design be commercialized, we would predict that the system will be adopted and self-sustaining in the market because of how it fulfills a medical need. As mentioned in our introduction, about "35% of U.S. adults age 40 years and older had evidence of balance dysfunction" [1] which can lead to fear of falling and sedentary lifestyle. Adults age 40 years and older are typically members of society who have disposable income and are more likely to make purchases that improve their quality of life. By having a user base that is 35% of this demographic, we believe we will have enough consumers to purchase our product. Additionally, the technology that is developed for this project has multiple other uses for balancing motions such as standing and running, which is another chunk of the market. Additionally, there are no devices that currently exist on the market that are capable of correcting gait for people with balance disorders. Therefore, we will likely not have a lot of competition in this sector.

2. Is the system so likely to succeed economically that planetary or social systems will be worse off?
Though we expect the product to succeed economically, we expect it to succeed in a very niche portion of this market. Only people with vestibular disorders that experience balance dysfunction will be using this device, and so it will not be applicable to the majority of the US population. As we don't expect most Americans to purchase this device, we don't expect that this device will be mass manufactured, which can harm planetary systems through waste, maintenance, and over-use of resources. Without the need for large manufacturing plants, we don't expect large amounts of waste to be released into residential areas, which can cause a multitude of health and environmental problems. Thus, we believe the public cost of our product will be very low. Additionally, the purpose of the device is to allow those with balance issues resulting from vestibular disorders to walk without fear of falling. We don't believe this product could be leveraged against other socio-economic identities, as it can only improve the health of the user.

3. Is the sustainable technology resilient to disruptions in business as usual?
We also believe that our technology will be incredibly resilient to disruptions in business as usual. On the surface level, our device is being used in a research setting only, so the sustainability of it does not rely on many outside sources. It is solely a singular device being used by very limited people for a very limited purpose, and there's nothing else out there on the market that fits it's role or that could affect its viability. On a slightly higher level, we designed this device under extreme conditions already: working entirely remotely in a team where we couldn't have access to hardly any physical resources. This has made it so that our design and its supplementary materials are all suitable to be used and understood both on an online platform as well as by a variety of people. Therefore, we believe not only is our sustainable technology resilient to disruptions in business as usual, but it is even more resilient than many other products out there because of the difficult circumstances we had to fight through to create it.

F.5. Ethical Decision Making

As engineers, there is a responsibility to record accurate data, prioritize safety, and make decisions objectively when making a product to be used for research purposes. The Code of Ethics was followed closely for this project to ensure accurate results, proper verification and transparency for our product.

Our main ethical prioritization revolved around safety. Whether our device functions fully or fails miserably, the main thing we can have control over is making sure that it is safe. Whether that be by covering wires to make sure that the risk of electrical shock is minimal, trimming excess material to make sure that the risk of entanglement between the device and the wearer is minimal, or limiting the size of the device to make sure that the wearer would have minimal negative side effects of wearing it, safety was always our number one priority for everything we did on this project. In addition, whether our results be favorable or not, we were sure to be honest and true to our job as engineers to report our results accurately. Our motivation with this project was to create a device that was capable of helping people with vestibular disorders to correct their gait and live healthier and safer lifestyles. It was not motivated by the grades we received or by fame or by anything else. Therefore, we recorded results from our verification and validation tests accurately and attempted to follow our objective requirements and specifications when making decisions as opposed to making design decisions that weren't as pricey or that required less work. For example, we originally wanted to buy the MMR metatracker IMUs which would have been cheaper, arrived sooner, and given us more time to work on and complete the creation of the device. However, the qualities of this IMU were not up to our engineering standards and, although, personally, buying the MMR would have cost us less money and led to us having to not work as hard, we chose to move forward with the Xsens DOT IMUs as they allowed us to create the best product possible despite us having to work harder to implement it as well as it's late arrival meaning we also had to do so in a shorter amount of time.