Final Report: Dynamic Balance Device

Biomedical Engineering 301

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Abstract

Approximately 30% of post-stroke patients experience Spatial Neglect Syndrome, which impairs balance and increases their fall risk, slowing their recovery [1]. In addition to this, 75% of physical therapists suffer from musculoskeletal disorders developed during their practice [2]. Current rehabilitation methods are either rudimentary–such as a yardstick–or expensive, such as a large stationary display. Previous designs for this project were too heavy for the client to use repeatedly, resulting in wrist and elbow pain, or lacked durability. This project aims to develop a lightweight, durable, and cost-effective Dynamic Balance Device to improve visuomotor training and balance rehabilitation for post-stroke patients. The final design includes a fixed length carbon shaft with an integrated measurement system along the length. There will be a 56.25 cm^2 display at the end and a sensor system. Carbon fiber was selected as the material choice due to its lightweight characteristics and unmatched strength-to-weight ratio. Testing includes MTS analysis to measure elastic modulus and toughness, while qualitative surveys will be completed to assess comfort, perceived weight, and ability to hold for an extended period of time. This device provides a cost-effective and client-centered solution to the limitations presented by existing devices, while also providing unique modes of implementation to improve patient outcomes.

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Introduction

A. Problem Statement

Physical therapists rehabilitating stroke patients use devices to improve visual scanning and balance training. Current devices for stroke rehabilitation are either rudimentary–such as a yardstick with a sticky note at the end–bulky, or unaffordable. The client, Mr. Daniel Kutschera, a physical therapist, helps patients to regain strength and balance following a stroke. The client seeks to develop a device that is lighter and more complex than his previous design, which weighed 0.36 kg. The device should be multi-functional so as to help patients with varying degrees of need and be effective in the rehabilitation treatment.

B. Motivation

Falls are the leading cause of injury-related death in adults aged over 65, attributed to decreases in balance and mobility that come with old age [3]. Among stroke survivors, about 30% of patients experience Spatial Neglect Syndrome or lose vestibular sense, leading to falls that set back their recoveries [1]. Physical therapists have found successful therapies to retrain the brain to better understand these spatial relationships following stroke, however, these methods often involve using devices that may pose injury risks to therapists. The length of physical therapy devices can make them feel heavier and cause fatigue more quickly, even when the actual weight of the device is relatively low. Approximately 75% of physical therapists develop musculoskeletal disorders during their careers [2]. Two previous BME design teams have worked on this project and have had success creating relatively lightweight devices, however, they have lacked durability and are still perceived as heavy. Complex devices for stroke rehabilitation typically cost between $12,000-$22,000, making them inaccessible to many physical therapists [4]. The client for this project, Mr. Daniel Kutschera, saw a need to improve the complexity and ergonomics of devices used for Spatial Neglect Syndrome rehabilitation. The goal of this project is to create a device that implements both auditory feedback and color-coded visual feedback to these devices to aid in the rehabilitation of stroke patients suffering from Spatial Neglect Syndrome.

C. Existing Devices

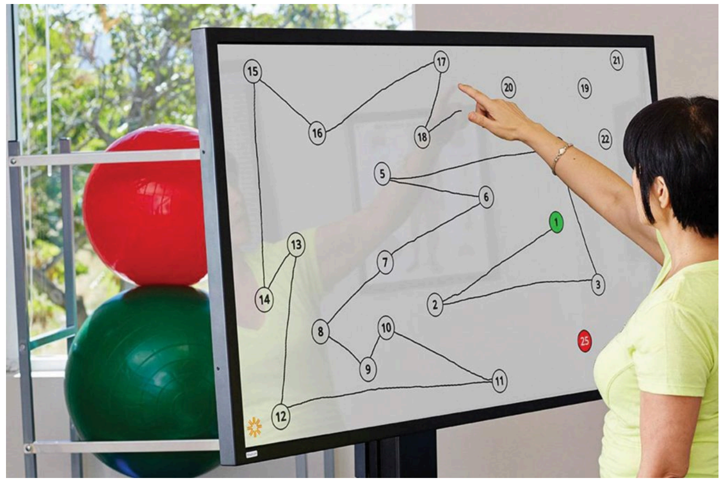


Figure 1: Bioness Integrated Therapy System [5]

The Bioness Integrated Therapy System (Figure 1) is an existing device used to improve cognitive training, hand-eye coordination, peripheral awareness, reaction time, and standing tolerance [5]. This device is a touch screen that has a variety of programs that are used to personalize the therapy to match where the patient is at in their recovery. It also allows for the physical therapist to use both of their hands to help support the patient. This device typically ranges from $12,000 to $22,000 depending on whether the therapist would like additional accessories or needs additional permits [4].

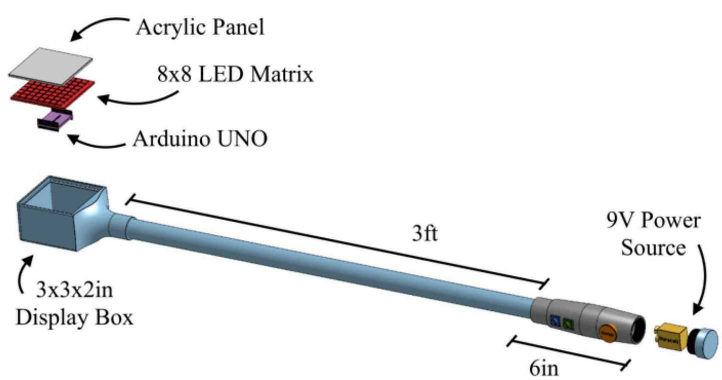


Figure 2: Previous design from Fall 2024 created by another BME design team [6]

Previous BME design teams have developed devices to improve upon the client's current device, a yardstick with a sticky note at the end. These devices (Figure 2) have implemented electronic components with changing colors and buttons to control the colors shown on the display screen. However, these devices have been too heavy for practical use and have not been durable enough to withstand the therapy that the client performs.

Background

A. Background Research

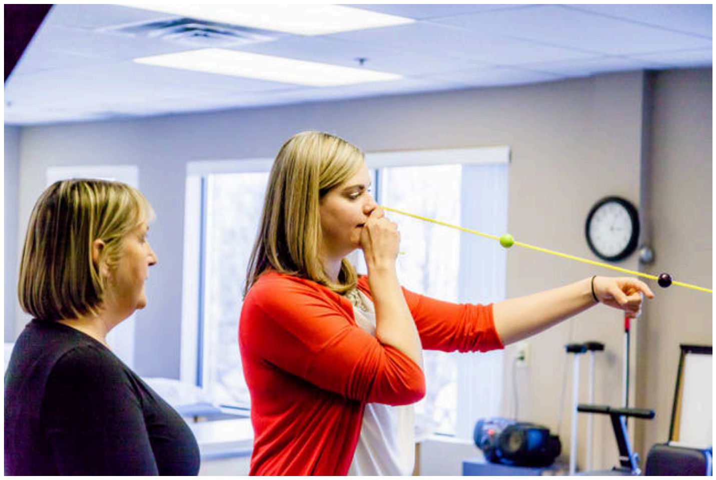


Figure 3: Visuomotor Training [7]

Stroke patients are at an increased risk for developing Spatial Neglect Syndrome, resulting in a lack of understanding the representation of space and impaired spatial attention [8]. Specifically, about 30% of patients that have suffered from stroke experience Spatial Neglect Syndrome and patients that have had damage to the right hemisphere of the brain are at an even greater risk [1]. Spatial Neglect Syndrome often results in an increased risk for falling due to difficulty balancing that can significantly slow down the recovery process.

Physical therapists use targeted therapies with patients suffering from Spatial Neglect Syndrome to improve spatial relationships. One of these therapies is called visuomotor training which involves the physical therapist asking the patient to reach towards an object to help the patient's brain relearn depth perception and spatial relationships [7]. This therapy typically lasts about 15 minutes per patient and is performed by the physical therapist 5-6 hours a day, 5 days a week. Due to the fact that the device needs to be held in an extended outward position in front of the patient, physical strain is prevalent in many physical therapists.

B. Design Research

In order to create a device that can be comfortably held for prolonged periods of time, it is necessary that the bulk of the electronics are distributed in a way that makes the perceived weight of the device less than or equal to the actual weight [9]. Therefore, the electronic components must be at the end of the device with the handle in order to reduce the effects of torque. To help stabilize the device, a counterweight will be added, likely the electronic components, to help stabilize the mechanism for the physical therapist. A counterweight works by providing an equal and opposite torque on one side of the device to balance the torque generated from the opposite side [10].

Auditory and visual feedback provide clear, real-time feedback to confirm that the patient has successfully completed the task properly. Capacitive sensors are a helpful electronic device that can be implemented to provide ease for both the client and patient. These sensors are activated by introducing stimuli close to them. The capacitive sensors vary in sensitivity which will make it so that the patient does not need to perfectly reach the desired length for the sensors to accurately activate. These sensors would then be used to either trigger a speaker or visual component to successfully provide feedback.

C. Client Information

Mr. Daniel Kutschera is a physical therapist for ThedaCare, an acute stroke clinic in Fitchburg, WI. His therapy specializes in stroke rehabilitation, specifically for patients suffering from Spatial Neglect Syndrome.

D. Design Specifications

The device must meet specific requirements outlined by the client and follow the Product Design Specification outlines (see Appendix A). The device must be at least 10% lighter than the previous design which weighed 0.36 kg and the electronic display at the end must be 7.5 cm across or 56.25 cm^2 to ensure that it is large enough for the patient to see it. The electronic display must have the ability to display red and blue with two different settings. The first setting must switch between red and blue, where red indicates the patient reaching toward the device with their right hand and blue indicates reaching toward the device with their left hand. The second setting must switch between these colors randomly so that the patient can practice visual scanning while identifying the color of the display. The shaft of the device must be at least 61 cm long as this provides a challenge for the patient to reach to the end of the device without being too long. The shaft of the device must also include a measurement system that allows the client to perform a functional reach test with his patients to track their progress. The device must also be made using a material that can be frequently sanitized and durable. The total cost of the project must not exceed $500.

Preliminary Designs

A. Overall Designs

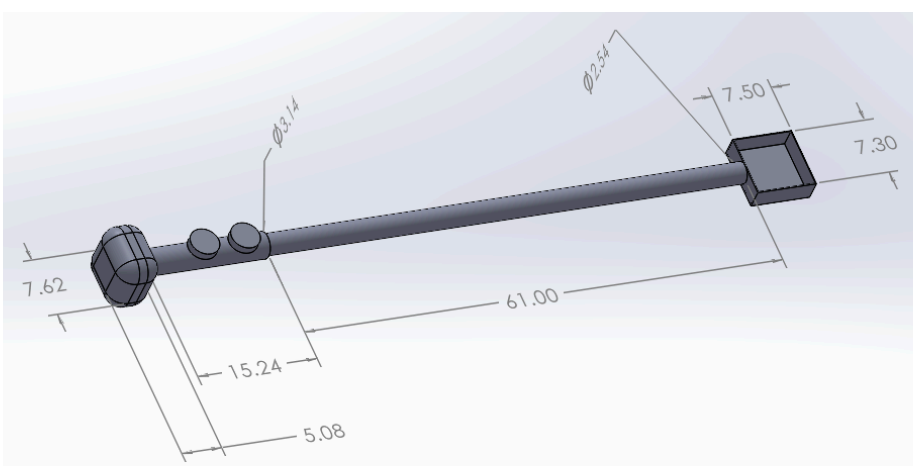


Figure 4: Fixed Length Shaft Design

This design features a rod connected to a display at the end. The handle includes a button to change the color of what is being displayed, and a switch to turn the display on and off. The control buttons are placed at the end of the handle so they are easily accessible, while the power button is placed lower so it is not accidentally activated in use. The display is the visual output component, using a screen to display different colors and shapes. This design is customizable to what the client would like to show based on the options that are coded by the group.

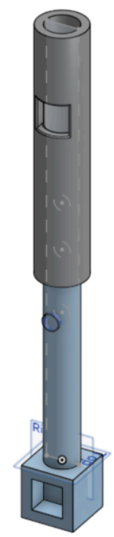


Figure 5: Push Button-Pin Shaft Design

This design includes a cylindrical upper casing display mounted vertically onto the rod. The casing includes the electronic components. This design extends from the base fixed-length shaft by adding new sections to extend and maintain the length of the device. This aspect of the design can make it more accessible for some users. The visual display fits into the box on the lower end, similarly to the fixed-length shaft. The control buttons are also placed similarly to the fixed-length design.

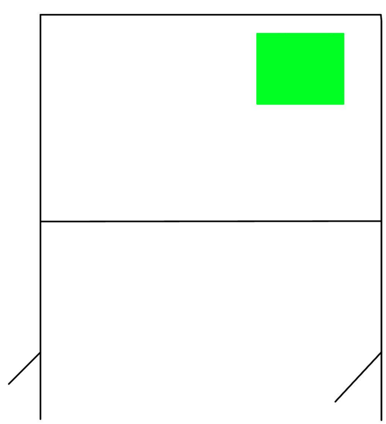


Figure 6: Hands-Free Board Design

This design is a shift from the handheld design to a larger stationary panel display. There is a board mounted on supports, with a large screen that could display anything the client wanted to use. The design shown here is a shape, which would allow the patient to practice pressing buttons or tracking shapes. This design shows a high visibility, complex output making it suitable for patient use. This will be a hands free design that lowers the burden on the provider, but the display is a much more expensive option and could be beyond the scope of this project.

B. Auditory Feedback Designs

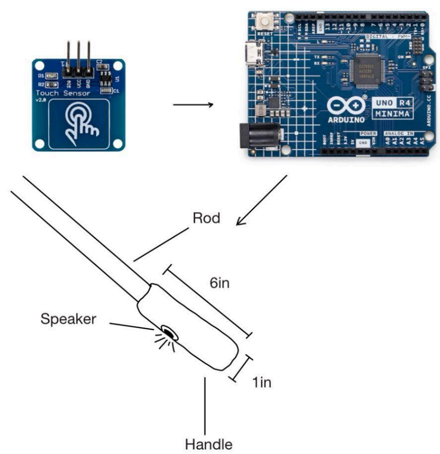


Figure 7: Sensor-Activated Speaker Design

The first design considered for the auditory feedback matrix is the Sensor-Activated Speaker. This design incorporates a capacitive touch sensor to allow a hands free activation of the speaker. When the user touches the sensor, the Arduino, along with the microcontroller code in Arduino IDE, activates a small speaker embedded in the handle. This design emphasizes simplicity and low effort for the user, so the client can focus on supporting the patient. This design also allows for a variety of different sounds to be programmed into the device, allowing for different feedback.

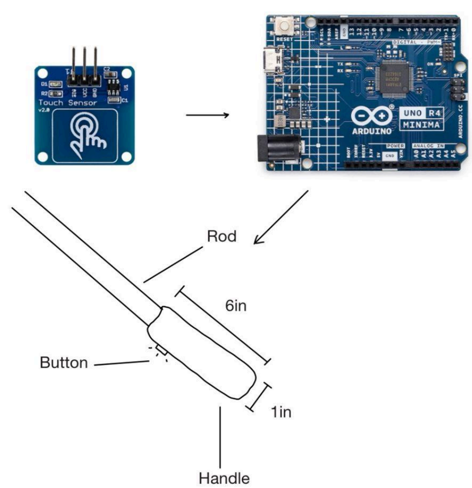


Figure 8: Sensor-Activated Noisemaker Design

The second design replaces the capacitive touch sensor with a physical push button. The button is wired to the circuitry containing the Arduino. When the sensor is activated, the coding in Arduino IDE will be such that the auditory feedback noisemaker is triggered. An advantage of this design is that it is more lightweight than the speaker, but this requires more precise 3D modeling and fabrication.

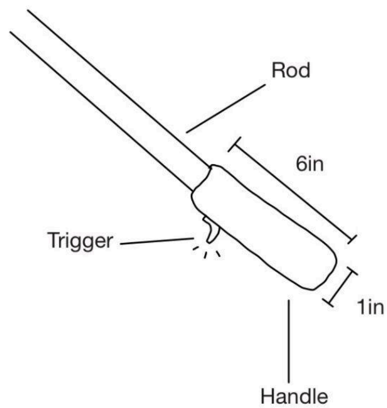


Figure 9: Manual Trigger Design

This design uses the trigger as the input for the auditory feedback. As opposed to the capacitive sensor or button, the pulling of the trigger activates the mechanism. This design of the handle could be more ergonomic for the user. However, this design requires the most effort for the user and is the least effective at achieving the ease of use and effectiveness the client requires.

C. *Material Designs*

Figure 10: Carbon Fiber Design [11]

Carbon Fiber is an extremely lightweight material with high strength to weight ratio, making it well suited for a project that is prioritizing comfort for the client when supporting the device. It has high tensile strength, ranging from from 3,500 MPa to over 7,000 MPa allowing it to withstand repeated use without deformation [12]. Carbon fiber is also sterilizable and will not be affected by disinfectant wipes. Carbon fiber cannot be 3D printed, so this will have to be carefully machined in the TEAM lab, especially since it is an expensive material.

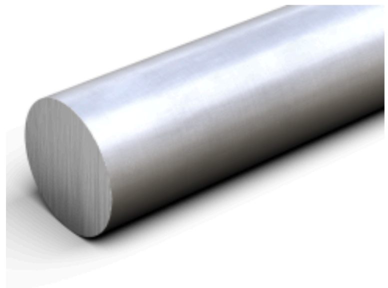


Figure 11: Aluminum Alloy Design [13]

Aluminum alloy is a strong but lightweight material commonly used for medical application. It offers mechanical strength while being easy to fabricate. Aluminum naturally forms a passive oxide layer which results in improved corrosion resistance. The tensile strength of a common aluminum alloy ranges from 228-572 MPa [14]. This material requires machining in the form of the mill and lathe.

Figure 12: PVC Tubing Design [15]

PVC tubing is a lightweight thermoplastic material, which will be easier to source and fabricate with. It is resistant to moisture so it will withstand sterilization and daily use. PVC will be easy to machine with a mill or lathe. PVC has lower tensile strength, about 31-60 MPa, so it will be easier to work with, but may not be as durable as needed [16].

Preliminary Design Evaluation

A. *Overall Design Matrix*

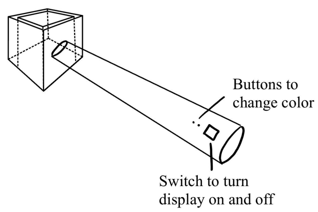
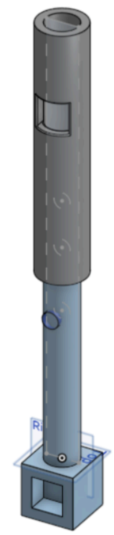
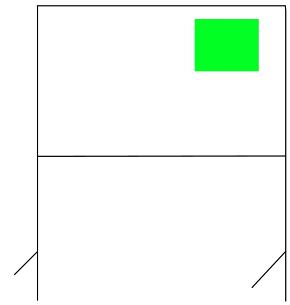
Designs		Design 1: Fixed Length Shaft 		Design 2: Push Button Pin Shaft 		Design 3: Hands Free Board 	
Rank	Criteria	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
1	Weight (25)	4/5	20	4/5	20	5/5	20
2	Durability (25)	5/5	25	4/5	20	4/5	20
3	User Comfort (20)	4/5	16	4/5	16	3/5	12
4	Ease of Fabrication (15)	5/5	15	3/5	9	2/5	6
5	Safety (10)	5/5	10	4/5	8	4/5	8
6	Cost (5)	5/5	5	4/5	4	1/5	1
Total:			81		77		67

Table 1: Overall Design Matrix

Criteria:

Weight (25):

Weight evaluates numerically and experimentally how heavy the final design will be perceived by the user. The product is intended to be in use while the client is physically supporting patients, so a manageable weight is a key factor in how easily this can be done. In addition, if the device is too heavy it might degrade faster or fail at attachments. Weight will be evaluated as better or worse than the previous design, which was deemed too heavy. If the device is too heavy and it hinders the client's ability to support the patient, the patient could face a safety risk. Since weight impacts comfort, durability, and safety, it is given the highest weighting of the criteria.

Durability (25):

Durability refers to the device's ability to withstand use for 8 hours a day 5 days a week. The device will be durable if it does not require frequent servicing. Durability also specifies that the attachments should be especially secure, since the previous designs have failed at the attachments. Durability can include the material strength and also the integrity of the design. If the device is not durable enough the device will be unsafe for the patient, so durability is very important for the chosen design.

User Comfort (20):

User comfort evaluates how easy it will be for the user to effectively use the final product. This includes how much the user's hand needs to extend to change the color of the light displayed at the end of the device, the grip used to hold the device for extended periods of time, and the user's confidence with using the final product for therapy. This criteria is important because this design has previously lacked comfortability for the user.

Ease of Fabrication (15):

Ease of fabrication describes the complexity of the design and evaluates how complicated the design would be to fabricate. This includes any 3D printing, machining, and circuitry. This criteria is important in order to determine if the proposed design would be able to be fabricated during the timeframe for this project and with the given resource constraints. However, this criteria is not the most important as there is only one prototype being fabricated opposed to multiple that need to be easily replicated.

Safety (10):

Safety describes the potential risk of injury due to sharp edges, exposed circuitry, etc. in order to choose a design that reduces the risk of injury for the user. This criteria is weighted low as all of the design ideas will have the circuitry safely enclosed and include rounded edges in order to avoid harming the user.

Cost (5):

Cost evaluates the expense for fabricating each design. This criteria is weighted the lowest because all of the designs have a similar complexity and will easily remain in the budget provided. The overall cost will ultimately be determined by the material chosen which will be evaluated in the material matrix.

Score Explanation

Regarding weight, the hands-free board scored the highest, due to the physician not needing to hold the board up during its usage. For durability, the fixed length shaft scored the highest due to a lower amount of openings compared to the push button pin shaft. For user comfort, the fixed length shaft and push button pin shaft scored the highest due to their maneuverability and weight dispersion. For ease of fabrication, the fixed length shaft scored the highest, due to the singular main piece that holds up the bulk of the material. It removes steps that would be necessary with either other design. For safety, the fixed length shaft scored the highest due to how the physician can use and hold it, along with how it doesn't need to have a button where things could possibly get stuck. For cost, the fixed length shaft scored the highest due to needing fewer mechanical components.

B. Auditory Feedback Design Matrix

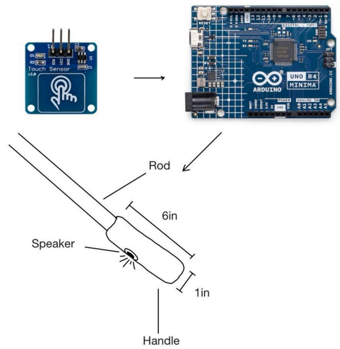
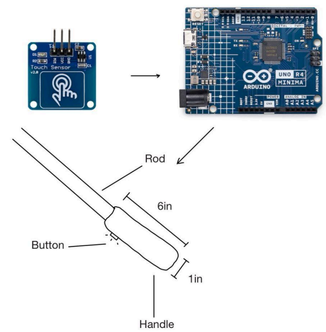
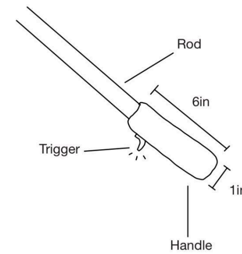
Designs		Design 1: Sensor-activated Speaker 		Design 2: Sensor-Activated Button 		Design 3: Manual Trigger 	
Rank	Criteria	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
1	Weight (35)	3/5	21	4/5	28	4/5	28
2	Ease of Use (30)	5/5	30	5/5	30	3/5	18
3	Ease of Fabrication (20)	4/5	16	2/5	8	4/5	16
4	Sound Variability (10)	5/5	10	3/5	6	3/5	6
5	Cost (5)	3/5	3	3/5	3	5/5	5
Total:			80		75		74

Table 2: Auditory Feedback Design Matrix

Criteria:

Weight (35):

Weight is ranked as the most important criterion because excessive weight was a significant issue identified by the client in previous iterations of the device. Since the auditory feedback system is an additional feature being integrated into the existing design, it is essential that it does not increase the overall weight of the device by a large amount. The selected components must be lightweight and compact to ensure that the final prototype is lighter than previous versions.

Ease of Use (30):

Ease of use refers to the level of additional input required from the physician in order to activate or receive auditory feedback. The device should operate intuitively and integrate seamlessly into therapy sessions without requiring extra switches, buttons, or manual inputs. This ensures that the clinician can focus entirely on supporting and monitoring the patient rather than managing device controls. This criteria is weighted highly in order to prioritize patient safety and so as to not give extra work to the client.

Ease of Fabrication (20):

Ease of fabrication evaluates how complex it would be to integrate the auditory feedback system into the existing device architecture. This includes considerations such as modifying current circuitry, writing and debugging additional code, integrating new sensors or output components, such as a speaker, and producing any required 3D-printed housings or mounts.

Sound Variability (10):

Sound variability refers to the system's ability to adjust volume or tone to accommodate different patient needs. For example, patients with hearing impairments may require higher volume levels or specific frequency ranges to perceive feedback effectively, that may be too loud for other patients. Additionally, varied sounds for positive or negative feedback can potentially improve patient outcomes. Although customizable auditory feedback would enhance usability and inclusivity, it is not essential for basic device functionality. Therefore, this criteria is weighted lower than core functional considerations such as weight and ease of use.

Cost (5):

Cost is assigned the lowest weight because the project does not have strict financial constraints. The client has provided a flexible budget, allowing design decisions to prioritize performance, reliability, and usability over price. Furthermore, the potential design options are expected to fall within a similar cost range, reducing the impact of cost differences on decision-making. Therefore, cost will likely not be a determining factor.

Score Explanation

The design matrix uses the criteria above to determine the best design. For weight, both the sensor-activated button and manual trigger scored the highest due to the lower amount of components. For ease of use, both the sensor-activated speaker and the sensor-activated button scored the highest due to the sensor-based, automatic activation. For ease of fabrication, the sensor-activated speaker and manual trigger scored the highest due to the addition of new parts into the device. For sound variability, the sensor-activated speaker scored the highest due to its availability with other sound modules. For cost, the manual trigger scored the highest, due to the lack of as many electronic components as the other designs. Overall, the sensor-activated speaker scored the highest.

C. Material Design Matrix

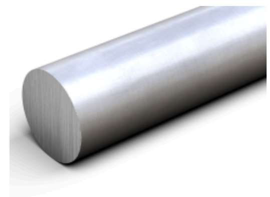
Designs		Design 1: Carbon Fiber 		Design 2: Aluminum Alloy 		Design 3: PVC Tubing 	
Rank	Criteria	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
1	Weight (40)	5/5	40	2/5	16	3/5	24
2	Durability (30)	5/5	30	5/5	30	4/5	24
3	Ease of Fabrication (15)	1/5	3	3/5	9	5/5	15
4	Ease of Engraving (10)	2/5	4	4/5	8	4/5	8
5	Cost (5)	3/5	3	4/5	4	5/5	5
Total:			80		67		76

Table 3: Materials Design Matrix

Criteria

Weight (40):

Weight is ranked as the most important criteria because excessive weight was the primary concern raised by the client regarding the previous prototype. A reduction in weight is therefore critical to improving overall usability. The selected material must be as lightweight as possible while still meeting strength requirements. This will improve user comfort and reduce physical strain, particularly in a clinical setting where the device will be used repeatedly throughout the day. Additionally, lowering the weight contributes to patient safety by minimizing the risk of injury if the device is dropped or mishandled.

Durability (30):

Durability is ranked as the second most important criteria due to issues with structural failure in previous prototypes. The final design is expected to have a minimum life in service of one year with minimal maintenance. Therefore, the selected material must possess sufficient strength in order to not bend or break due to bending stresses from normal use. It should also demonstrate resistance to wear and impact from patients that can be encountered in a clinical environment. Ensuring durability will increase longevity and overall performance of the device.

Ease of fabrication (15):

Ease of fabrication is given a slightly lower weighting because the design requirements involve minimal complex manufacturing processes. The material will be purchased in tubular form, reducing the need for most fabricating techniques. Any additional fabrication such as cutting, drilling, or finishing will be carried out using tools available in the TEAMLab on campus. Although the fabrication process will be straightforward, the material should still be compatible with available tools and processes to ensure safe and accurate construction of the prototype.

Ease of Engraving (10):

Ease of engraving evaluates how effectively measurement markings can be permanently applied to the material. The final prototype must incorporate a clear and accurate measurement system so that the client can collect reliable data during functional reach tests. The material should allow for precise engraving, etching, or marking without compromising structural integrity. While this is an important feature for usability and data accuracy, it is not weighted as highly because alternative marking methods such as vinyl decals, adhesive scales, or stenciling can be used if direct engraving is outside of the scope of this project.

Cost (5):

Cost is assigned a lower weighting because performance characteristics such as weight and durability are of greater importance for this project. As only a single prototype will be manufactured, material cost does not significantly impact the overall design. Furthermore, the client has provided a flexible budget, allowing material selection to be guided primarily by functionality rather than price constraints. However, cost is still considered to ensure responsible purchasing choices and to maintain the potential for future scalability if additional units are to be made.

Score Explanation

This design matrix also uses the criteria above to determine the best design. For weight, carbon fiber scored the highest, due to its low relative density. For durability, carbon fiber and aluminum alloy scored the highest due to their high tensile strength. For ease of fabrication, the PVC tubing scored the highest, due to how it can be worked on with multiple CNC machines. For ease of engraving, aluminum alloy and PVC tubing scored the highest due to the compatibility they have with mills. For cost, the PVC tubing scored the highest, due to its availability and price per gram.

Proposed Final Design

The proposed final design combines aspects from each of the listed matrices. The fixed-length shaft is implemented as the bulk of the design, constructed with carbon fiber. The handle will contain an internal compartment for storage of the power source, as well as buttons to turn the display on and off and change the colors of the display. The sensor activated speaker will be implemented in the box at the end of the carbon fiber tubing. This device will use a sensor activated speaker to perform a tactile, immediate response when a reach test is performed by the client in the physical therapy setting. The LED component will also be kept in this end portion, allowing for different colors to be displayed. The LED will be compatible with an Arduino microcontroller that will allow for simple commands to be transmitted [16]. Overall, the device will prioritize maintaining a light weight, being ergonomic, stable, affordable, and easy to use, being ideal for clinical and therapeutic settings that perform visual and balance training with patients.

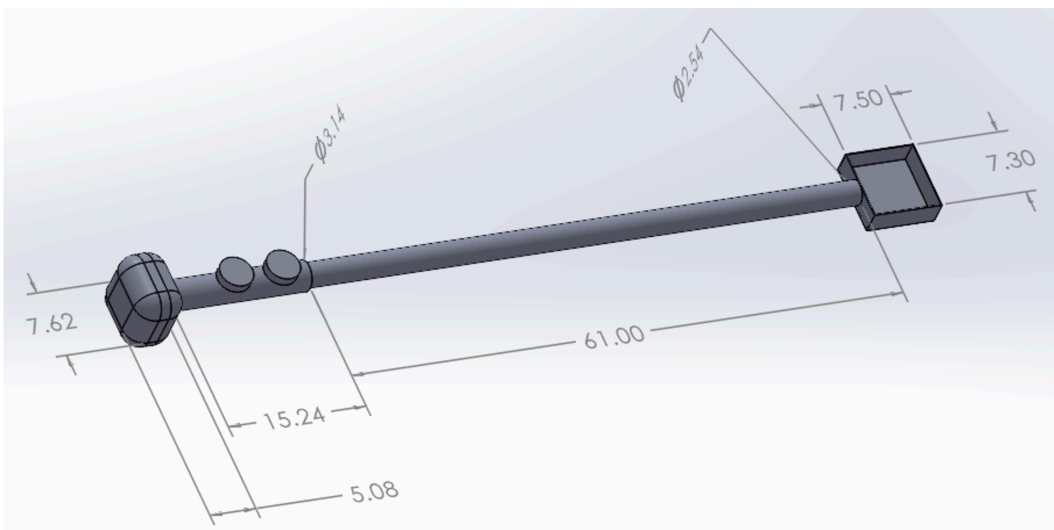


Figure 13: Proposed Final Design.

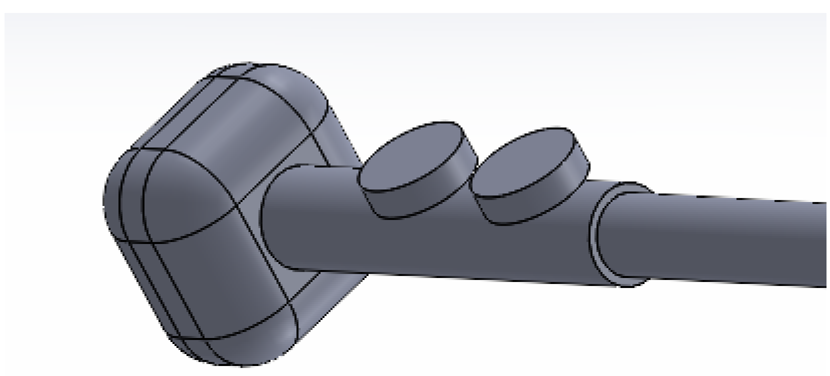


Figure 14: Preliminary device handle. Contains an on/off button and a button to change the display color.

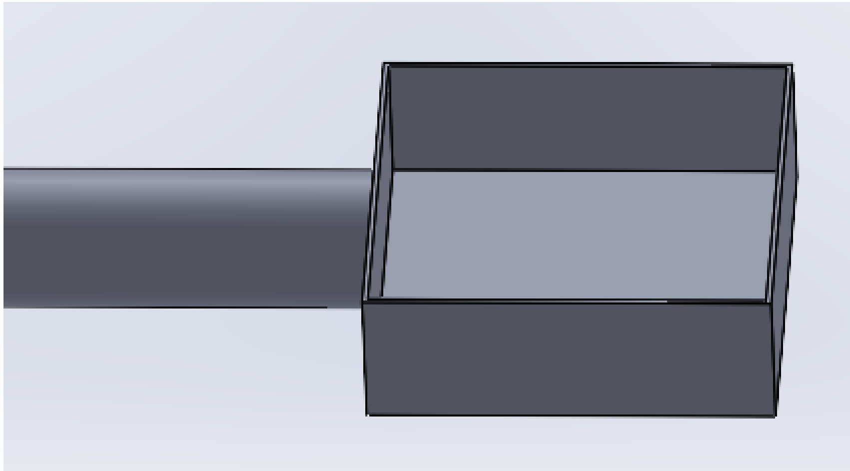


Figure 15: Preliminary visual display section of device with room for the LED display.

Fabrication

A. Materials

1 meter long carbon fiber was used for the rod portion of the prototype. Carbon fiber was chosen due to its expected lightweight yet durable properties.

The HC-SR04 Ultrasonic sensor was used after testing of the capacitive sensor proved to not be sensitive enough for these purposes. This sensor was chosen because it was small enough but sensitive enough. It was also readily available for testing and the group was already familiar with its use. Ultrasonic sensors detect objects by emitting high-frequency sound waves and measuring the time it takes for the echo to return, which made it easy to print the exact distance the input was on the serial monitor. This proved to be very useful for the functional reach test mode.

Arduino Nano was chosen as the microcontroller for this project due to its small size. The Nano was compared to the UNO the group already had and proved to be just as capable at about ¼ of the size. The small size was important not only for weight contributions but also was the determining factor of being able to fit the circuitry in the armband.

Adafruit Neopixel 8x8 LED pixel matrix is flat and lightweight. This display only has one input which simplifies the circuitry. It was chosen based on client requirements that the display be bigger than previous prototypes. It also satisfied client requirements of being able to show many different colors, and the brightness is easy to adjust through the software to accommodate all patients' visual capabilities.

B. Methods

First the handle and display were 3D printed out of carbon fiber reinforced PLA. In order to avoid complicated supports the handle was printed without the holes for the buttons, which allowed for the exact dimensions to be decided after it was determined how much space was required for both the buttons and their soldered legs. These holes were eventually cut out using a drill press and filed for precision. The carbon fiber rod was cut using a saw. After these components were prepared the back of the display and sensor were soldered, and the free side of those wires were fed down the carbon fiber rod and handle and soldered onto the perf board with the Arduino Nano. Each wire was labeled and the circuitry was fabricated according to the circuitry diagram seen in Figure 15. Note that the battery, arduino, and perf board are housed in the arm band on the shoulder and the display and ultrasonic sensor are located at the top of the carbon fiber rod. Each connection on the perf board was checked using a multimeter to ensure accurate connections and that there were no short circuits. Finally the Arduino code was written based on the logic flow diagram seen in Figure 16. The full circuitry fabrication protocol can be found in Appendix E.

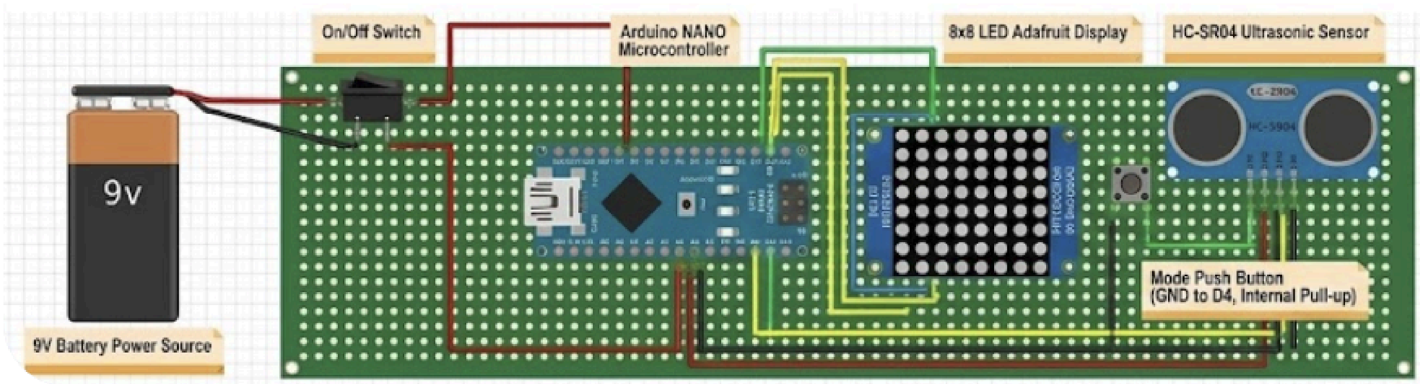


Figure 16: Circuit diagram showing all components on perf board with pin out specifications

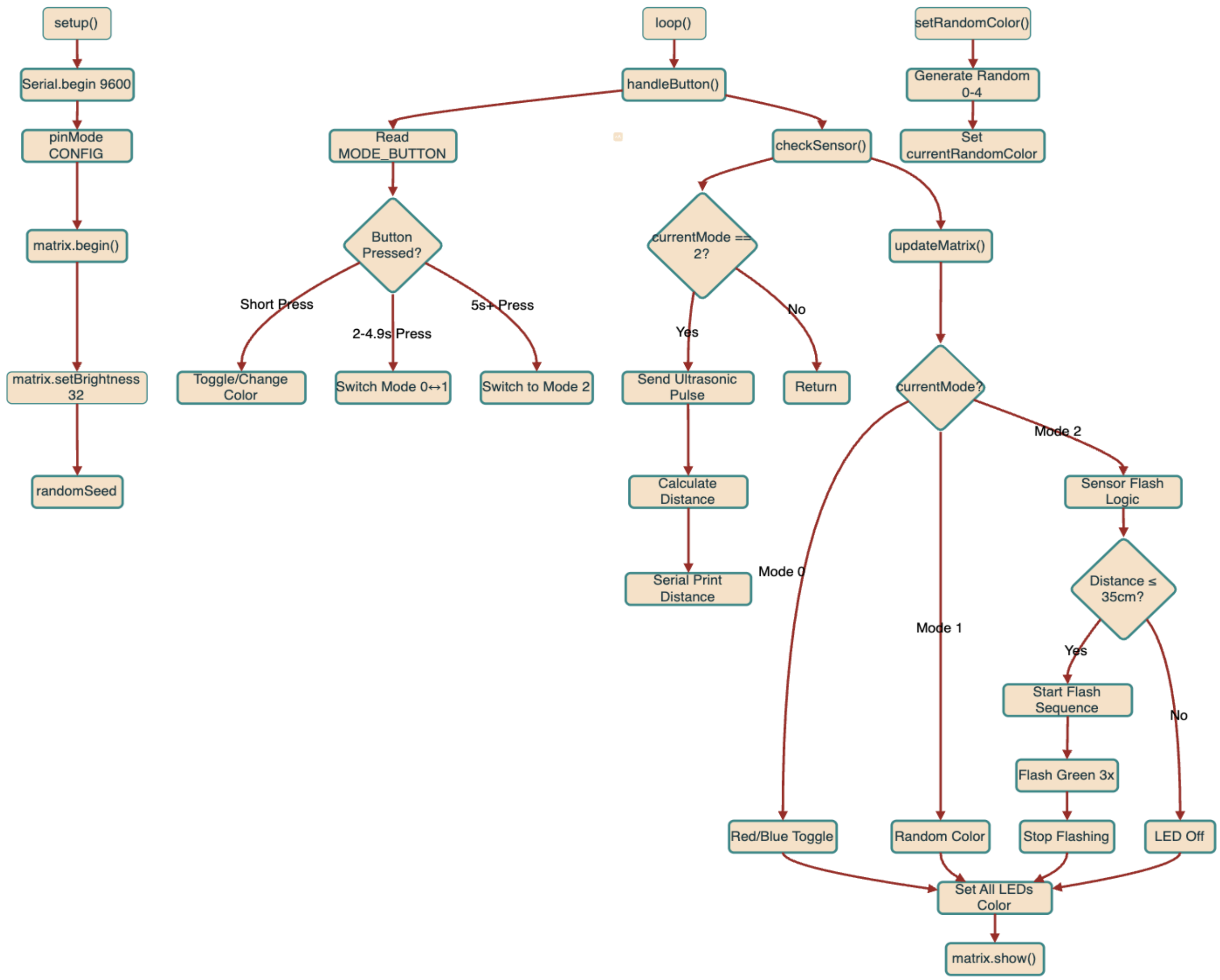


Figure 17: Logic diagram corresponding to Arduino IDE code

C. Final Prototype

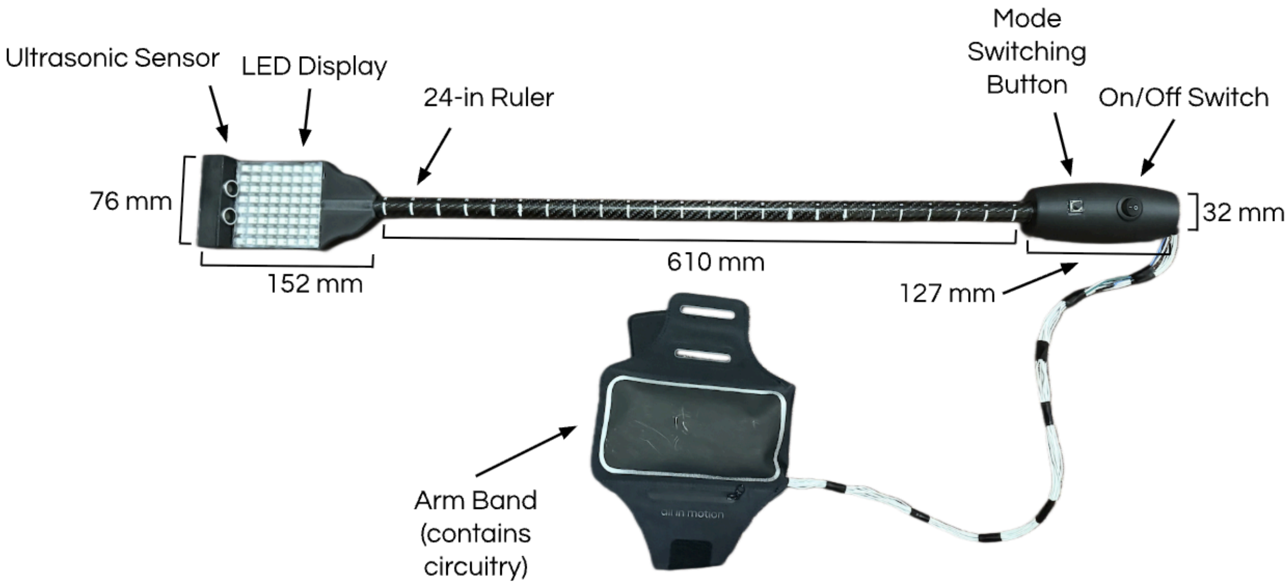


Figure 18: Final prototype with all components and dimensions

The final prototype features the carbon fiber rod attached on one side to the handle, the other side to the display and sensor, housed in a 3D printed casing. The circuitry is fed through from the display and ultrasonic sensor down the carbon fiber rod, with the microcontroller and battery in the arm band. Not shown here, the final design features all wires tightly wrapped with electrical tape. The handle has a power on/off button and a tactile button which changes the mode the device is in. The carbon fiber rod has 24 inches of measurement labeled with the paint and sealed with top coat as specified by the client.

Testing and Results

Tests were performed to evaluate both mechanical strength and improvement in comfort while using the prototype and weight perception. MTS testing was done using a 3-point bending setup seen in Figure 19. The test was repeated on 3 different samples and the results can be seen in Figure 20. Fatigue testing was also performed with 14 participants to evaluate the PDS criteria of perceived weight being lower than the previous prototype (see Appendix A). Each subject was instructed to hold out the prototype at a 90 degree angle, and tape was marked on the wall at their beginning position. Significant deviation from this taped line was considered failure. The subjects then held the device as long as they could before failing, and every 30 second increment they were asked various questions (see Appendix D). The next test was the dynamic portion, in which they waved the prototype in an arch motion and answered the same questions. The testing was then repeated with the Dynamic Balance Device instead of the previous semester's prototypes. This data was then summarized in Figures 21-24. The expected outcome was a variance in subject comfort using each prototype, and the results of where subjects felt the most discomfort will be used in future efforts to remodel the handle for improved comfort. All testing was found to be statistically significant, and p-values, where applicable, can be found in figure captions.

Figure 19: MTS 3-point bending setup

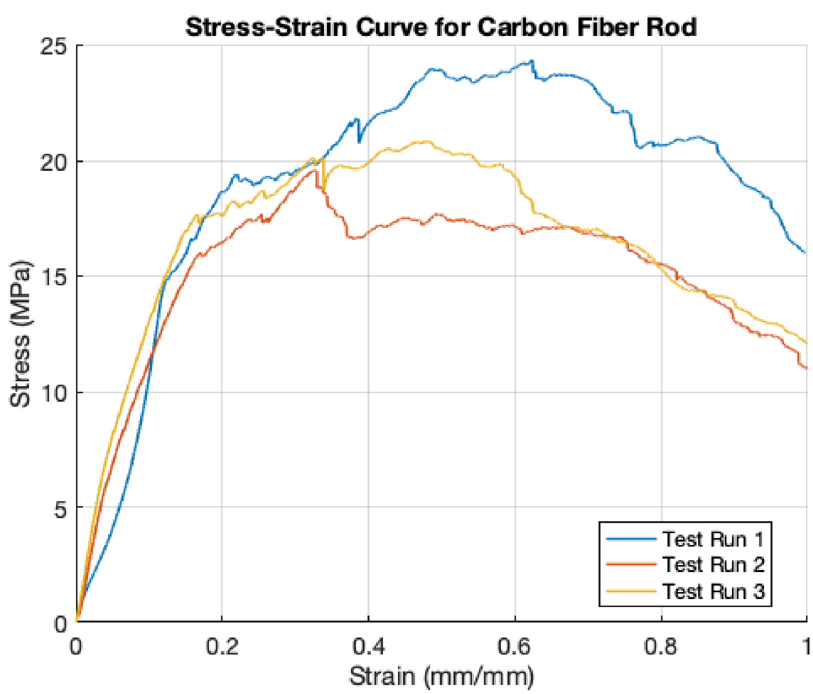


Figure 20: MTS testing results shown in a stress vs. strain curve, with average Elastic modulus = Average elastic modulus: 105.667 MPa. Maximum stress before plastic deformation: 15.776 MPa. Maximum deflection before plastic deformation: 2.88 mm

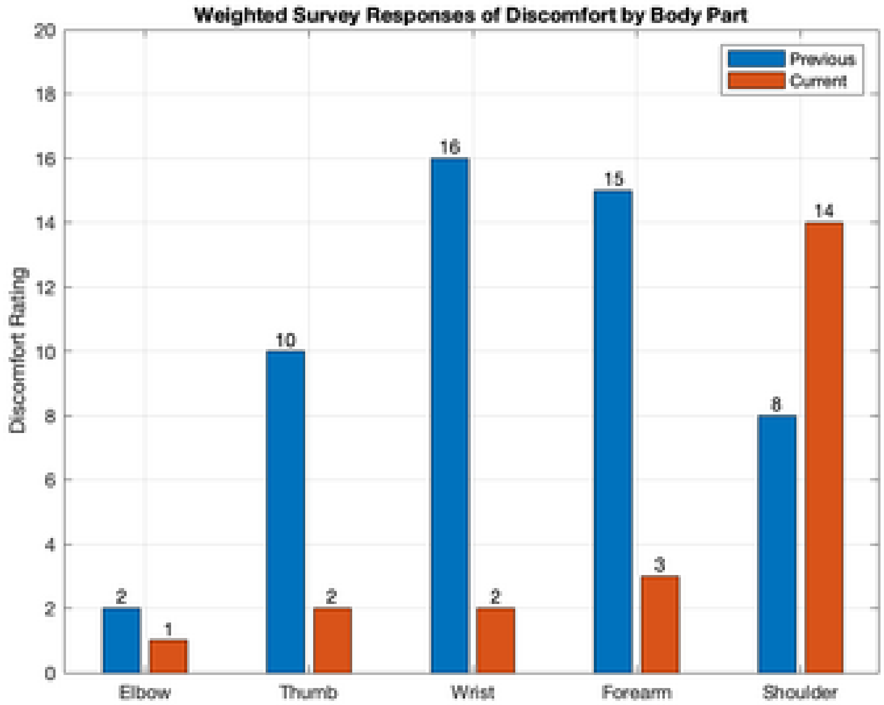


Figure 21: Weighted survey responses of discomfort by body part

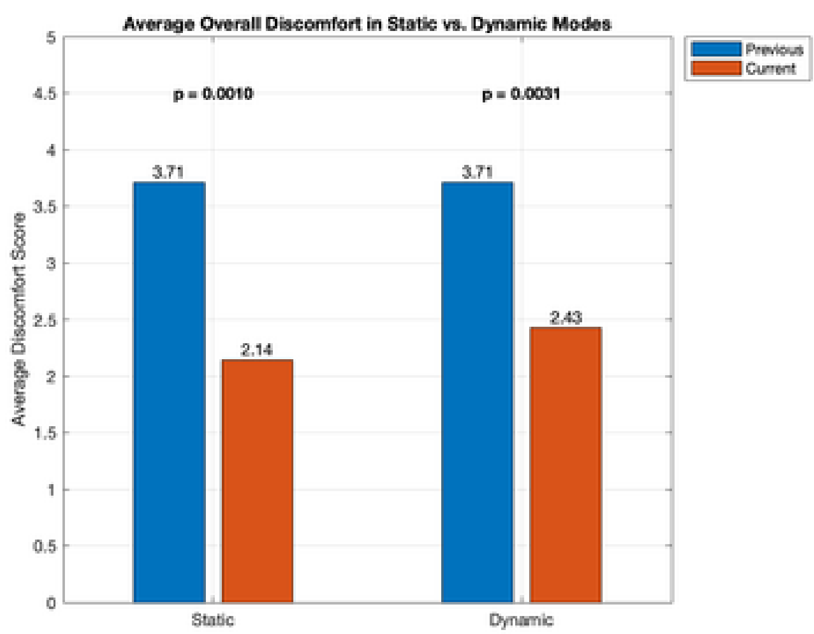


Figure 22: Average overall discomfort in static vs. dynamic modes, with p=0.001, 0.0031

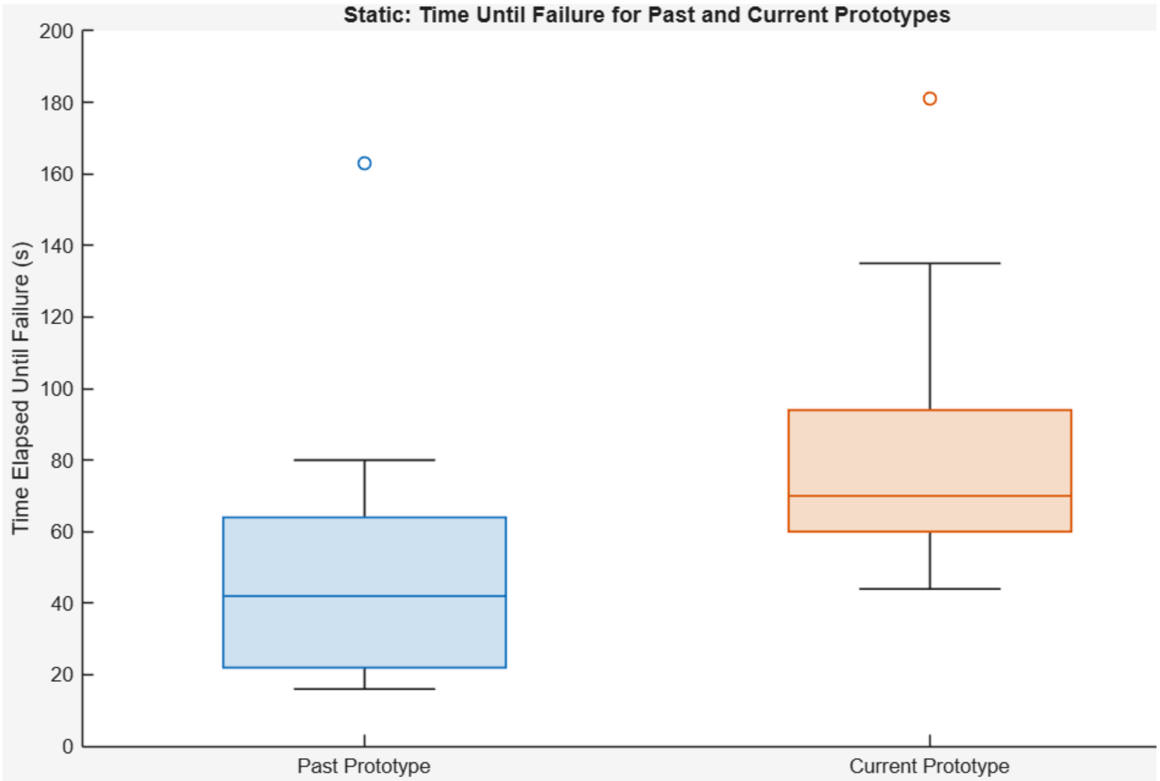


Figure 23: Time until failure for past and current prototype during static testing portion, p = 8.25e^-6

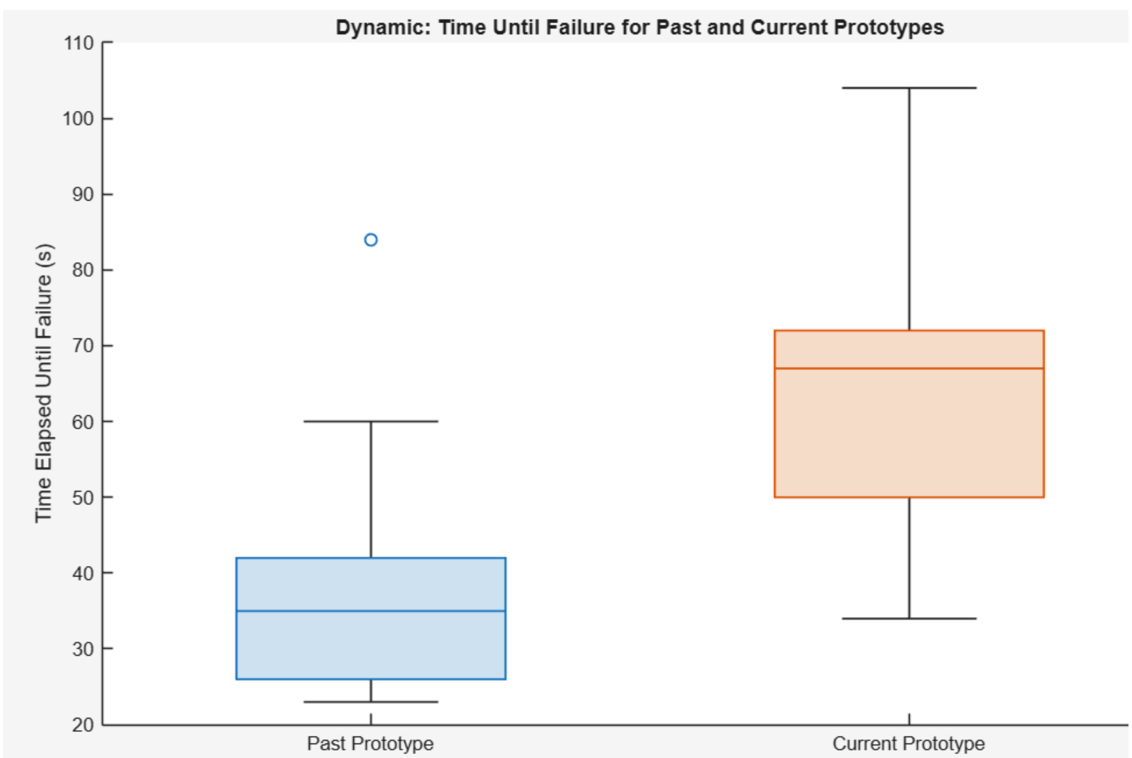


Figure 24: Time until failure for past and current prototypes during the dynamic testing portion, p = 4.69e^-6

Discussion

A. Implications of Results

The results of mechanical and usability testing support that the final design meets its primary objectives of strength, durability, and improved ergonomics for the clinician. MTS testing demonstrated that the carbon fiber material can withstand stresses well beyond those expected during typical clinical use, indicating the device is unlikely to bend or deform under repeated loading or its own weight over time. In addition, fatigue testing showed a statistically significant increase in the amount of time participants could hold the device until failure, both statically and during movement, when compared to a previous prototype ($p = 8.25 \times 10^{-6}$ and $p = 4.69 \times 10^{-6}$). Survey data also showed reduced discomfort in the thumb, wrist, forearm, and elbow, with all participants reporting lower overall discomfort using the current prototype. Although shoulder discomfort increased, this is likely attributable to testing conditions discussed in the limitations section rather than a flaw in the design itself.

Functional testing of the circuitry also demonstrated overall compatibility of the system, while identifying opportunities for improvement in future iterations. For example, interference between the passive speaker, chosen for its lightweight and small footprint, and nearby high-voltage LED reduced audio functionality, suggesting that future designs could benefit from an active speaker, electrically isolated placement, or addition of a capacitor to assist in signal filtering. Additionally, although the originally proposed capacitive sensors did not provide sufficient sensitivity and were replaced with an ultrasonic sensor, this design pivot led to the implementation of a Functional Reach Test mode that still fulfills the client's requirement for patient feedback while expanding the functionality of the device. Overall, these results demonstrate that the final prototype not only improved upon previous designs in comfort and performance, but also successfully met functional design goals.

B. Ethical Considerations

Ethical considerations played a significant role in the design of this device, particularly in promoting clinician safety and patient inclusivity. The device was developed with a lightweight, ergonomic design to minimize physical strain during prolonged use and reduce the risk of long-term musculoskeletal injury for clinicians. This is especially important because 1 in 6 physical therapists leave their practice due to musculoskeletal disorders developed at work, impacting provider well-being and the quality of patient care [17]. Inclusivity was also a key ethical consideration in the device's development, with therapy modes intentionally designed to accommodate a broader range of users and avoid excluding certain patient populations. For example, the alternating color mode was modified from a red/green color scheme to red/blue to improve accessibility for individuals with color vision deficiencies, reflecting universal design principles and a commitment to equitable rehabilitation outcomes. These modes can also be entirely modified to suit patient needs through small modifications to the software.

C. Sources of Error

One limitation of this study was the testing methodology used during fatigue testing, as participants used the previous prototype first and the current prototype second. This likely introduced effects that contributed to the increased shoulder discomfort for the current prototype due to cumulative fatigue rather than the device itself. As a result, discomfort scores for the current prototype may have been inflated, suggesting its ergonomic performance may be even better than the recorded data suggests. In future testing, this source of error could be reduced by randomizing prototype order between participants or incorporating breaks between trials. Another limitation relates to the accuracy of the ultrasonic sensor used in the circuitry. Because the sensor relies on reflected sound waves, it is most effective when a patient's hand approaches the sensor orthogonally. While this introduces variability in device response, the limitation can be mitigated through user training and clinician awareness during operation, and future design iterations could explore alternative sensing methods to improve reliability.

Conclusions

The goal of this project was to develop a cost-effective, clinician-centered rehabilitation device that improves upon the weight, comfort, and durability limitations of previous prototypes. This need is particularly significant given that approximately 75% of physical therapists experience work-related musculoskeletal disorders [2], highlighting the importance of reducing physical strain in clinical tools. The final design addresses this by incorporating a carbon fiber structure and relocating circuitry to an external arm band, resulting in a device that is approximately 20% lighter than earlier iterations and significantly more comfortable for extended clinical use.

Future work would include the integration of an active or digital speaker to add audio functionality. Additionally, based on survey feedback, the handle could be redesigned by creating finger grooves or use of a textured material, reducing the risk of the device slipping out of the user's hand. The perceived weight could be reduced even further by using a longer rod and moving the handle upwards to allow for a counterweighting system. Furthermore, the device could be made with a rechargeable battery, making it easier for the clinician to charge every night rather than waiting for the battery to die. Lastly, the device's functionality could be improved with the integration of an app that would allow the clinician to create profiles for each patient and record their progress, create custom modes for their needs, and more. Together, these improvements would further enhance the device's clinical utility, accessibility, and long-term usability in neurorehabilitation settings.

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Appendix

Appendix A: Product Design Specifications

Dynamic Balance Device

Product Design Specifications

BME 301

February 22, 2026

Client: Mr. Daniel Kutschera

Advisor: Professor Ohnsorg

University of Wisconsin-Madison

Department of Biomedical Engineering

Team:

Katherine Sattel (Team Leader)

Therese Kalt (Communicator)

Noor Awad (BSAC)

Freyja Heggeland (BWIG and BPAG)

Function:

An estimated 30% of patients who have suffered from stroke experience Spatial Neglect Syndrome or lose vestibular sense, leading to falls that set back their recoveries [1]. Therefore, it is important that clinicians have devices that help patients practice balance and retrain neural networks so they can complete daily activities such as walking independently. However, existing devices don't allow the clinician to easily assist the patient because they are too heavy, or are not complex enough to effectively improve balance. The goal of this project is to design a lightweight device that allows the patient to practice scanning and complete a functional reaching test using an electronic component. As opposed to the previous design of an aluminum pipe with an LED, this device will be multifunctional and durable for convenient use.

Client requirements:

- The design is significantly lighter than the previous prototype
- The prototype is durable and well constructed, especially where the electronic components attach
- Feedback elements, including auditory feedback
- At least a 7.5 cm diameter display so that it is visible for patients with limited eyesight
- Varying colors and target shapes on the display
- A ruler integrated into the device so that a functional reaching test can be performed
- A reusable device that can be easily sanitized with a wipe

Design requirements:

1. **Physical and Operational Characteristics**
    a. **Performance requirements**:

    The final design must assist the physical therapist in improving visual scanning and postural balance for post-stroke patients suffering from spatial neglect syndrome. It must have a display at the end of the shaft that has the ability to present a variety of colors. The final design must be able to withstand frequent use, every weekday for up to eight hours. The shaft must be a fixed length and durable while being a lightweight material that resists bending and deformation due to the load at the end of the shaft from the display. The rod and display must be able to withstand 10 N without permanently deforming more than ten degrees.

    b. **Safety**:

    The final design must be a strong and durable material to ensure the device is stable in the user's hand and prevents mechanical failure while in use. This material must also be lightweight to prevent strain for the therapist and allow attention to be focused on patient care while using the device. The electronic elements must be safely enclosed to reduce risk of injury or hazards associated with exposed circuitry. The final design must also not include any sharp edges that could potentially harm the therapist while using the device.

c. **Accuracy and Reliability**:

The final design must accurately display the correct color when prompted by the therapist. The shaft of the device must have an accurate measurement system to ensure the provider collects reliable data when performing the functional reach test [2]. The final prototype must also reliably provide auditory feedback when the patient accurately completes the task.

d. **Life in Service**:

The final prototype must last at least one year with minimal servicing. The device will be used frequently for up to eight hours a day and five days a week. The handle and shaft of the prototype must be durable in order to avoid service within the first year. The electronics and circuitry may need quick maintenance, such as changing batteries, but these replacements must be simple and quick to perform.

e. **Shelf Life**:

The final device will be used exclusively indoors. The prototype must withstand frequent sterilization, as it must be wiped down by a disinfectant wipe between patients.

f. **Operating Environmen**t:

This device will be used in indoor environments for physical therapy. The device will be non-porous, as it will be cleaned and sterilized frequently. The device should be resistant to common deterioration and fluid corrosion. As the device will be used very frequently, it is important that it remains sturdy and can withstand normal forces from impacting the floor of the physical therapy spaces. Patients will be interacting with the device, so for preventative measures in case the patients hit the device against something, it may need additional force resisting properties along the base of the rod.

g. **Ergonomics**:

This device will be used by a physical therapist to assist in the rehabilitation process with a patient who has experienced a stroke. The device must be able to be held in one hand, easily held, and easily maintained for at least 30 minutes, allowing the user to aid the patient if necessary. The colored target portion of the device should be easy to adjust and to have a control panel near the device's main interface near the handle.

h. **Size**:

The size of the rod should be a maximum of 1 meter in length. The display needs to be a target with at least a 7.5 cm diameter.

i. **Weight**:

The device needs to weigh under 0.5 kg with the majority of the weight located in the handle of the device to prevent fatigue for the client while they are holding it up. The user's perception of the weight is especially important, due to the higher torque load that comes with more weight allocated to the opposing end of the device.

j. **Materials**:

The materials for this device will need to be sterilized frequently with a disinfectant wipe, meaning they will need to be non-porous and able to undergo minimal maintenance without issue. The materials for the screen will need to be lightweight, waterproof, and have the ability to portray the main three primary colors, as per the interactive portion.

k. **Aesthetics, Appearance, and Finish**:

The device will have a professional and quality appearance. The device must be easy to clean and sterilize. The display portion of the device must display various bright colors. The design will also include measurement markings up to 1 meter, so the user and patient can both easily determine how far the patient can reach in any given condition.

2. **Production Characteristics**
   a. **Quantity**:

   There will be a total of one unit constructed for this project. More prototypes and development may be made in the future, but are outside the scope of this project.

   b. **Target Product Cost**:

   The target product cost will be within $500.

3. **Miscellaneous**
   a. **Standards and Specifications**:

   The final prototype must adhere to the regulations for a Class I medical device under FDA 21 C.F.R. Part 890 [3]. This device is classified as low-risk and therefore does not require any premarket approval by the FDA. The final prototype will contain electronic components and may be subject to IEC code 62353:2014 [4].

   b. **Customer**:

   The client is a doctor who specializes in neurological rehabilitation and physical therapy. The client intends to use the device daily, therefore, durability must be a priority. The previous prototype felt too heavy so lightweight material choices will be important. Additionally, the client will be using the device daily, for up to 8 hours per day, so it must be comfortable to hold for long periods of time. The device should appear more sleek and professional than the client's current set-up. The device must be intuitive to use and not have a steep learning curve.

c. **Client-related concerns**:

The device does not need to be sterile but should be able to be easily cleaned with a disinfectant wipe when necessary. The device must also be able to be used with one hand, allowing the physician to support the patient with the other, maximizing both physician and patient safety.

d. **Competition**:

Competition for this device includes the client's current solution, a 1 meter long PVC tube with a bright-colored laminated dot affixed to the end. This product is very rudimentary and was not intended to be a long-term solution. Additionally, a device currently on the market is the Bioness Integrated Therapy System [5]. This solution provides a variety of assessments for the patient as well as testing balance, reach, and their Romberg score. The client currently has this system in their clinic, however, this device is static and does not allow the patient to move while using it, limiting its efficacy in helping patients get back to performing daily tasks with ease and regaining full-body awareness.

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Appendix B: Expense Documentation and Budget

Total Budget for the Semester: $500

Full spreadsheet:

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
Carbon Fiber Tube	1m long, 20mm outer diameter, 18mm inner diameter	CHZDPP	B0DJJTX3SQ	Amazon	B0DJJTX3SQ	3/9/2026	1	$48.49	$48.49	https://www.amazon.com/dp/B09Q8513TH?smid=A2E498AYYT4IOM&ref_=chk_typ_imgToDp&th=1
3D Filament	3D Printed portion	Makerspace	n/a	Makerspace	n/a	3/18/2026	1	$5.17	$5.17	https://making.engr.wisc.edu/
metal rod	metal rod	Makerspace	n/a	Makerspace	n/a	3/18/2026	1	$0.00	$0.00	https://making.engr.wisc.edu/
arm band	arm band	All in Motion	197543111024	Target	082-02-2568	4/8/2026	1	$11.66	$11.66	https://www.target.com/p/phone-armband-fits-up-to-6-1-34-phone-black-all-in-motion-8482/-/A-88001461#lnk=sametab
Super glue	Clear super glue	Gorilla	524277820380	Target	081-22-7899	4/8/2026	1	$5.39	$5.39	https://www.target.com/p/gorilla-glue-6g-clear-gel-twin-pack/-/A-75571463#lnk=sametab
Vinyl Sheet	Vinyl Sheet	Makerspace	n/a	makerspace	n/a	4/11/2026	1	$0.15	$0.15	https://making.engr.wisc.ed

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Vinyl Stickers	Inch markers	Shunyinlai	B0FLXM9H8C	Amazon	B0FLXM9H8C	4/12/2026	1	$14.75	$14.75	https://www.amazon.ca/SHUNYINLAI-Adhesive-Stickers-Waterproof-Organizing/dp/B0FLXM9H8C?th=1
Electronic Components										
Capacitive Touch Sensor Switch	Sensor	Arduino	TTP223B	Ebay	TTP223B	3/9/2026	1	$8.32	$8.32	https://www.ebay.com/itm/177296732195?mkevt=1&mkpid=0&emsid=e11400.m144671.l197929&mkcid=7&ch=osgood&euid=86ed426ee7ca46569227cca485a0c2c8&bu=45748113567&exe=0&ext=0&osub=-1%7E1&crd=20260309080259&segname=11400
9V Battery	Battery	Vetco Electronics	VUPN8981	TEAMLAB Makerspace	VUPN8981	3/18/2026	1	$0.75	$0.75	https://vetco.net/products/vupn8981_9v_battery_connector_-_straight_style?_pos=1&_sid=c92b9fb78&_ss=r
Tactile switch	Button	Vetco Electronics	TEA-5144	Shopify	TEA-5144	3/9/2026	2	$0.89	$1.78	https://vetco.net/products/vupn1504_tact_switch_66m

										m_5mm_through_hole?_pos=1&_sid=067499b42&_ss=r
Waterproof Switch	On/Off switch	Vetco Electronics	NTE-54-250W	Shopify	NTE-54-250W	3/9/2026	1	$9.99	$9.99	https://vetco.net/products/nte-54-250w_dpdt_waterproof_rocker_switch_on_-_off_-_on_20a?_pos=1&_sid=71077f9dc&_ss=r
Speaker Module	Speaker	Vetco Electronics	VUPN6344	Shopify	VUPN6344	3/9/2026	2	$4.21	$16.21	https://vetco.net/products/vupn6344_piezo_speaker_module_for_arduino_buzzer_d46?_pos=1&_sid=1dcb64e19&_ss=r
Arduino Nano	Microcontroller	Arduino	A000005	Amazon	A000005	3/25/2026	1	$21.69	$21.69	https://www.amazon.com/Arduino-A000005-ARDUINO-Nano/dp/B0097AU5OU
Braided Cable Sleeve	Cable Sleeve	Alex Tech	704256851316	Amazon	B071G5L29C	4/11/2026	1	$17.47	$17.47	https://www.amazon.com/dp/B071ZV6MZ2?ref=cm_sw_r_cso_sms_apin_dp_JP43A6Z4SH98KFJY3VX6&ref_=cm_sw_r_cso_sms_apin_dp_JP43A6Z4S

										H98KFJY3VX6&social_share=cm_sw_r_cso_sms_apin_dp_JP43A6Z4SH98KFJY3VX6&rsd=gMVRFUE4GUEBR%2BAOcp1A%2BpdY96Chi4lhEP6aErCf6%2FfVT0gaw8aI9YDFSNSIJCyafaEY%2Fdx4xb8t2In7Z4wkIxjig8GQRRimIwE6iOFL191mj%2Fbn371jkYs%3D&edk=AQIDAHi1lw%2FM8UbbSMD9ScOOFEmBMHMthHeEhqDaQYPJUAX3jQG2fYTcgSzrqY9%2BO5iOcYhQAAAAfjB8BgkqhkiG9w0BBwagbzBtAgEAMGgGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMamkU8zaQqKWwsiLwAgEQgDu%2FwZln%2BASA7Bz09TMWfsSh0HV8WBK1aUGjK8cDpKfSHPw4StE36a8o2xFKFX0A4HBkUxd

										LKXERNb7lZg%3D%3D&th=1
								TOTAL:	**$161.82**	
								Remaining Budget:	**$338.18**	

Appendix C: Arduino Code

Note: the Adafruit_NeoPixel package must be installed to properly run this code. The following package can be found and downloaded from GitHub, found here: https://github.com/adafruit/Adafruit_NeoPixel.

```
#include <Adafruit_NeoPixel.h>

#define LED_PIN 11

#define NUM_LEDS 64

#define MODE_BUTTON 7

#define TRIG_PIN 3

#define ECHO_PIN 5

Adafruit_NeoPixel matrix(NUM_LEDS, LED_PIN, NEO_GRB + NEO_KHZ800);

// --- MODES ---

// 0 = Red/Blue Toggle Mode

// 1 = Random Mode

// 2 = Sensor Mode (Flashes Green at 35cm)

int currentMode = 0;

// Toggle state

bool redState = true;

// Button timing

unsigned long buttonPressTime = 0;

bool buttonWasDown = false;

// Random color tracking

uint32_t currentRandomColor;

int lastChoice = -1;

int currentDistance = 0;

const int distanceThreshold = 35; // Bumped threshold to 35 cm

bool isFlashing = false;

int flashCount = 0;

unsigned long lastFlashTime = 0;
```

```
bool flashState = false;

// Timing variables

unsigned long lastUpdate = 0;

int updateInterval = 50;

unsigned long lastSerialPrint = 0;

void handleButton();

void checkSensor();

void updateMatrix();

void setRandomColor();

void setup() {

  Serial.begin(9600);

  pinMode(MODE_BUTTON, INPUT_PULLUP);

  pinMode(TRIG_PIN, OUTPUT);

  pinMode(ECHO_PIN, INPUT);

  matrix.begin();

  matrix.setBrightness(32);

  matrix.show();

  randomSeed(analogRead(A1));


  Serial.println("System Started... 3 Modes Available.");

}

void loop() {

  handleButton();

  checkSensor();

  updateMatrix();

}

//BUTTON

void handleButton() {
```

```
bool buttonDown = (digitalRead(MODE_BUTTON) == LOW);

if (buttonDown && !buttonWasDown) {

  buttonPressTime = millis();

  buttonWasDown = true;

}

if (!buttonDown && buttonWasDown) {

  unsigned long heldTime = millis() - buttonPressTime;

  // LONG PRESS

  if (heldTime >= 5000) {

    currentMode = 2;

    isFlashing = false; // Reset flash state if switching into this mode

    Serial.println("Switched to: SENSOR MODE (35cm Threshold)");

  }

  // LONG PRESS (2 to 4.9 Seconds)

  else if (heldTime >= 2000) {

    if (currentMode == 0) {

      currentMode = 1;

      setRandomColor();

      Serial.println("Switched to: RANDOM MODE");

    } else {

      currentMode = 0;

      redState = true;

      Serial.println("Switched to: RED/BLUE TOGGLE");

    }

  }

  // SHORT PRESS (Under 2 Seconds)

  else {

    if (currentMode == 0) {
```

```
        redState = !redState;
        Serial.println("Color Toggled");
      }
      else if (currentMode == 1) {
        setRandomColor();
        Serial.println("Random Color Changed");
      }
    }

    buttonWasDown = false;
  }
}
//RANDOM MODE
void setRandomColor() {
  int choice;

  do {
    choice = random(5);
  } while (choice == lastChoice);
  lastChoice = choice;
  switch (choice) {
    case 0: currentRandomColor = matrix.Color(255,0,0); break;
    case 1: currentRandomColor = matrix.Color(0,255,0); break;
    case 2: currentRandomColor = matrix.Color(255,255,0); break;
    case 3: currentRandomColor = matrix.Color(0,0,255); break;
    case 4: currentRandomColor = matrix.Color(128,0,128); break;
  }
}
```

```
//SENSOR LOGIC
void checkSensor() {
  if (currentMode != 2) return;
  digitalWrite(TRIG_PIN, LOW);
  delayMicroseconds(2);
  digitalWrite(TRIG_PIN, HIGH);
  delayMicroseconds(10);
  digitalWrite(TRIG_PIN, LOW);
  long duration = pulseIn(ECHO_PIN, HIGH, 30000);
  currentDistance = duration * 0.034 / 2;
  if (millis() - lastSerialPrint > 250) {
    Serial.print("Distance: ");
    if (currentDistance == 0) {
      Serial.println("Out of range");
    } else {
      Serial.print(currentDistance);
      Serial.println(" cm");
    }
    lastSerialPrint = millis();
  }
}
//UPDATE LED
void updateMatrix() {
  if (millis() - lastUpdate < updateInterval) return;
  lastUpdate = millis();
  uint32_t color = matrix.Color(0, 0, 0);
  if (currentMode == 0) {
    color = redState ? matrix.Color(255,0,0) : matrix.Color(0,0,255);
```

```
 }
 else if (currentMode == 1) {
  color = currentRandomColor;
 }
 else if (currentMode == 2) {

  // 1. Start the flash sequence if hand is detected
  if (!isFlashing && currentDistance > 0 && currentDistance <= distanceThreshold) {
   isFlashing = true;
   flashCount = 0;
   flashState = true;
   lastFlashTime = millis();
   Serial.println("Target Detected! Fast flashing sequence started.");
  }
  // 2. Handle the non-blocking flashes
  if (isFlashing) {
   if (millis() - lastFlashTime >= 150) { // Dropped to 150ms for a quick, short flash
    lastFlashTime = millis();
    flashState = !flashState; // Toggle lights on/off

    if (flashState == false) {
     flashCount++; // Count goes up every time the light turns off
    }
   }

   // Stop flashing after 3 full cycles
   if (flashCount >= 3) {
    isFlashing = false;
```

```
        flashState = false;
        currentDistance = 0; // Force a fresh sensor read so it doesn't loop instantly
      }
      // Apply the color based on whether we are currently "on" or "off" in the flash cycle
      color = flashState ? matrix.Color(0, 255, 0) : matrix.Color(0, 0, 0);

    } else {
      // Not triggered, sit completely off
      color = matrix.Color(0, 0, 0);
    }
  }
  for (int i = 0; i < NUM_LEDS; i++) {
    matrix.setPixelColor(i, color);
  }
  matrix.show();
}
```

Appendix D: Qualitative Testing Evaluation Form and Evaluation Methods

Link to form:
https://docs.google.com/forms/d/e/1FAIpQLSd3A79dlJpe5zix6pCuPhSksjfr_fmTCH-mJZsRNzyM0uUHrA/viewform

Results table:
https://docs.google.com/spreadsheets/d/1TGhTHoxKRbitWpMUwbCxP3SSlGUHgEEGkAxVTgBonA0/edit?resourcekey=&gid=327958055#gid=327958055

Protocol:

1. Have participants complete tasks as noted by the testing survey. Their responses will be recorded and summarized.
2. Both the device from Fall 2024 and the current device will be used, so the team can perform a t-test discussing the difference between the two.

Fatigue Testing Survey

1. How difficult was it to hold the previous device with your arm extended for 30 seconds?
    a. very easy
    b. easy
    c. not easy or difficult
    d. difficult
    e. very difficult
2. How long were you able to hold the previous device at one point until failure? (answer in seconds, round to the nearest second)
3. How difficult was it to hold the previous device in an arc for 30 seconds?
    a. very easy
    b. easy
    c. not easy or difficult
    d. difficult
    e. very difficult
4. How long were you able to move the previous device in an arc until failure? (answer in seconds, round to the nearest second)
5. Where on your body would you say you felt the most discomfort while using the previous device?
    a. Thumb
    b. Palm of hand

   c. Wrist
   d. Forearm
   e. Elbow
   f. Upper arm
   g. Shoulder
6. For the area in which you felt the most discomfort while holding the previous device, please rate that discomfort using the scale below:
   a. 1 - I did not feel any discomfort
   b. 2 - Barely uncomfortable
   c. 3 - Slightly uncomfortable
   d. 4 - Uncomfortable
   e. 5 - Very uncomfortable
7. How difficult was it to hold the current device with your arm extended for 30 seconds?
   a. very easy
   b. easy
   c. not easy or difficult
   d. difficult
   e. very difficult
8. How long were you able to hold the current device at one point until failure? (answer in seconds, round to the nearest second)
9. How difficult was it to hold the current device in an arc for 30 seconds?
   a. very easy
   b. easy
   c. not easy or difficult
   d. difficult
   e. very difficult
10. How long were you able to move the current device in an arc until failure? (answer in seconds, round to the nearest second)
11. Where on your body would you say you felt the most discomfort while using the current device?
   a. Thumb
   b. Palm of hand
   c. Wrist

   d. Forearm
   e. Elbow
   f. Upper arm
   g. Shoulder

12. For the area in which you felt the most discomfort while holding the current device, please rate that discomfort using the scale below:
    a. 1 - I did not feel any discomfort
    b. 2 - Barely uncomfortable
    c. 3 - Slightly uncomfortable
    d. 4 - Uncomfortable
    e. 5 - Very uncomfortable

Appendix E: Fabrication Protocol

Fabrication Plan for Final Prototype

A. Printing Materials

a. Download .3mf files from file repository
b. Ensure 3D printer settings align with the settings in the .3mf file
c. Print both
d. Remove supports and excess filament using pliers

B. Circuitry Fabrication

a. Acquire materials listed below:
   i. Arduino Nano
   ii. 9V battery
   iii. 1x Tactile Switch Button
   iv. DPDT Waterproof Rocker Switch 20A
   v. 8x8 LED Matrix
   vi. HC-SR04 Ultrasonic Sensor
   vii. Perf board
   viii. Flexible wires to connect circuit components

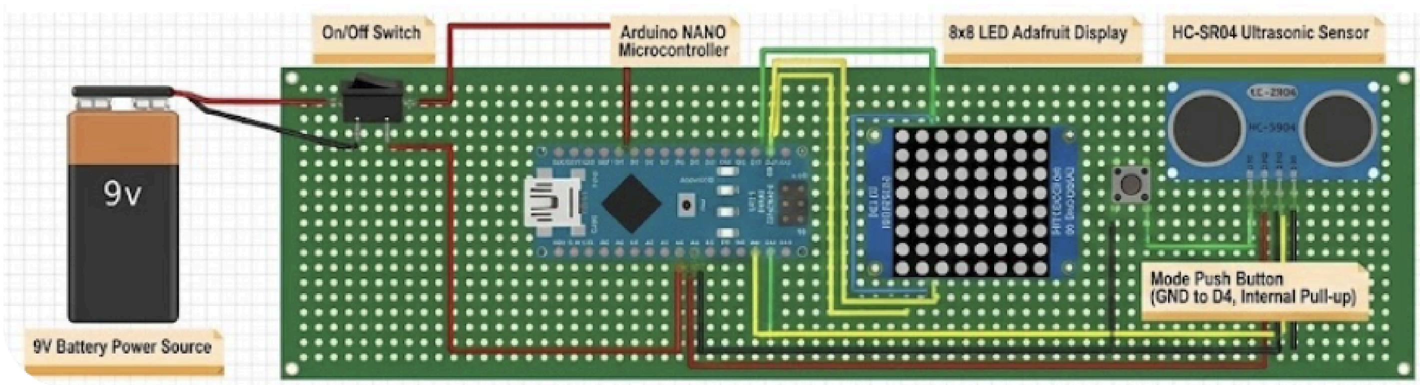

Figure 1: Fritzing diagram of circuitry

b. Construct Fritzing Diagram as shown.
   i. Connect red lead of the battery (+) positive lead of on/off switch, then, connect other lead of on/off switch to Vin pin of Arduino Nano, negative lead to GND
   ii. Connect Arduino 5V pin to the 5V rail of perf board, Arduino GND pin to GND on breadboard
      1. Use small wire to create "rails" on ends of bread board to ensure all components can be connected properly
   iii. Connect one leg of button to 5V rail and diagonally opposite leg to Digital pin 7
   iv. Connect Vcc pin of ultrasonic sensor to 5V rail, trigger pin to Digital pin 3, echo pin to Digital pin 5, and GND pin to GND rail

v. Connect Vcc of 8x8 LED matrix to 5V rail, and GND to ground rail. Connect input of LED to Digital pin 11
vi. Implementing code
    1. Cross check digital pin assignments to Arduino IDE definitions for both inputs and outputs
    2. Upload code (see Appendix C) to Arduino and double check for errors before turning power on. Optionally, the circuit can be tested with the Arduino powered by USB before the 9 V battery is in place.

C. Final Assembly

a. Gather the following materials:
    i. 1 m/3 ft long Carbon Fiber Rod
    ii. Clear super glue
    iii. Electrical tape
    iv. Frosted acrylic sheet (3 x 3 in., ¼ in thick)
    v. 3D printed components (see “Printing Materials” section for further instruction on 3D printed portions)
        1. Handle
        2. Display housing
        3. Sensor housing
    vi. Circuitry components (see “Circuitry Fabrication” section for further instruction on circuitry portion)
    vii. White paint
    viii. Numbered stickers
    ix. Running arm band
b. Machining:
    i. Use a drop saw to cut the carbon fiber rod to a length of 27.5 in.
    ii. Use a drill press to drill holes into the 3D printed handle. Follow RPM recommendations listed on machine for plastic material
        1. For the on/off switch, use 0.75 in. bit
        2. For the button, use 0.25 in. bit
    iii. Use small files to widen the drilled holes to the specific shape of the buttons to ensure they fit seamlessly into the handle
c. Assembly:
    i. Before connecting electronic components to Arduino Nano and perf board, run wires for display and ultrasonic sensor down the middle of the rod
        1. Ensure the display housing is affixed to the end of the rod before this step
    ii. Slide the handle onto the base of the rod
    iii. Run the buttons wires through the holes in the handle
    iv. Attach circuitry to the Arduino Nano and perf board in accordance with Section B: Circuitry Fabrication

v. Use superglue to permanently attach the handle, buttons, display housing, sensor housing, and acrylic panel over the LED
vi. Use electrical tape to cover the exposed wire running from the base of the rod to the arm band
    1. Optionally, use a woven wire cover prior to soldering the perf board connections
vii. Use white paint and numbered stickers to label a 24 in. ruler along the length of the rod
    1. Ensure that the numbers begin counting up from the handle toward the display
viii. Seal the paint and stickers using UV resin
ix. Optionally, use electrical tape to cover seams between 3D printed portions for a more polished appearance

Appendix F. All MATLAB Code for Data Analysis

```
D_out = 20.0;
D_in = 18.0;
L0 = 20.0;
A = (pi / 4) * (D_out^2 - D_in^2);
figure;
hold on;
strain1 = data1{:, 1} ./ L0;
stress1 = data1{:, 2} ./ A;
plot(strain1, stress1, 'LineWidth', 1.5, 'DisplayName', 'Test Run 1');
strain2 = data2{:, 1} ./ L0;
stress2 = data2{:, 2} ./ A;
plot(strain2, stress2, 'LineWidth', 1.5, 'DisplayName', 'Test Run 2');
strain3 = data3{:, 1} ./ L0;
stress3 = data3{:, 2} ./ A;
plot(strain3, stress3, 'LineWidth', 1.5, 'DisplayName', 'Test Run 3');
title('Stress-Strain Curve for Carbon Fiber Rod');
xlabel('Strain (mm/mm)');
ylabel('Stress (MPa)');
legend('show', 'Location', 'best');
xlim(0:1)
grid on;
hold off;

lower_strain1 = 0.0;
upper_strain1 = 0.120;
idx1 = (strain1 >= lower_strain1) & (strain1 <= upper_strain1);
lin_strain1 = strain1(idx1);
lin_stress1 = stress1(idx1);
fit1 = polyfit(lin_strain1, lin_stress1, 1);
E1 = fit1(1);
fprintf('Test Run 1: %.2f MPa\n', E1);
Test Run 1: 114.00 MPa
lower_strain2 = 0.0;
upper_strain2 = 0.1656;
idx2 = (strain2 >= lower_strain2) & (strain2 <= upper_strain2);
lin_strain2 = strain2(idx2);
lin_stress2 = stress2(idx2);
fit2 = polyfit(lin_strain2, lin_stress2, 1);
E2 = fit2(1);
fprintf('Test Run 2: %.2f MPa\n', E2);
```

```
Test Run 2: 93.42 MPa
lower_strain3 = 0.0;
upper_strain3 = 0.1469;
idx3 = (strain3 >= lower_strain3) & (strain3 <= upper_strain3);
lin_strain3 = strain3(idx3);
lin_stress3 = stress3(idx3);
fit3 = polyfit(lin_strain3, lin_stress3, 1);
E3 = fit3(1);
fprintf('Test Run 3: %.2f MPa\n', E3);
Test Run 3: 109.58 MPa
max_stress_3 = max(lin_stress3)
max_stress_3 = 16.8146
```

MATLAB script for discomfort by body part:

```
% --- Data ---

Elbow_old = 2; Thumb_old = 10; Wrist_old = 16; Forearm_old = 15; Shoulder_old = 8;

Elbow_new = 1; Shoulder_new = 14; Wrist_new = 2; Thumb_new = 2; Forearm_new = 3;

% --- Organize Data ---

% Column 1: Old | Column 2: New

data = [Elbow_old,   Elbow_new;

        Thumb_old,   Thumb_new;

        Wrist_old,   Wrist_new;

        Forearm_old, Forearm_new;

        Shoulder_old, Shoulder_new];

body_parts = {'Elbow', 'Thumb', 'Wrist', 'Forearm', 'Shoulder'};

% --- Plotting ---

figure('Color', 'w');

b = bar(data);

% Set Y-limit to 20

ylim([0 20]);

% --- Styling ---

set(gca, 'XTickLabel', body_parts);

ylabel('Quantity');

title('Body Part Comparison: Old vs. New');

legend('Old', 'New', 'Location', 'northeast');

grid on;

% Add data labels on top of bars
```

```
for i = 1:numel(b)
    xtips = b(i).XEndPoints;
    ytips = b(i).YData;
    labels = string(b(i).YData);
    text(xtips, ytips, labels, 'HorizontalAlignment', 'center', ...
        'VerticalAlignment', 'bottom');
end
```

MATLAB script for overall average discomfort:

```
% --- Raw Data ---
Vec_old_static = [2 4 4 4 3 4 3 3 2 5 3 5 5 5];
Vec_old_dynamic = [2 4 5 4 4 4 3 4 1 5 4 4 4 4];
Vec_new_static = [1 2 2 1 2 2 1 3 1 4 1 4 2 4];
Vec_new_dynamic = [1 3 1 2 3 2 1 3 2 3 3 4 2 4];
% --- Calculate Averages ---
avg_old_static = mean(Vec_old_static);
avg_new_static = mean(Vec_new_static);
avg_old_dynamic = mean(Vec_old_dynamic);
avg_new_dynamic = mean(Vec_new_dynamic);
% --- Statistical Testing (T-Tests) ---
% Compare Old vs New for Static
[h_static, p_static] = ttest2(Vec_old_static, Vec_new_static);
% Compare Old vs New for Dynamic
[h_dynamic, p_dynamic] = ttest2(Vec_old_dynamic, Vec_new_dynamic);
% Display results in Command Window
```

```
fprintf('Static Condition: p-value = %.4f\n', p_static);

fprintf('Dynamic Condition: p-value = %.4f\n', p_dynamic);

% --- Plotting ---

% Matrix: Rows are Static/Dynamic, Columns are Old/New

data_matrix = [avg_old_static,  avg_new_static;

               avg_old_dynamic, avg_new_dynamic];

figure('Color', 'w');

b = bar(data_matrix);

% Styling the axes

set(gca, 'XTickLabel', {'Static', 'Dynamic'});

ylabel('Average Discomfort Score');

title('Discomfort Comparison: Old vs. New');

legend('Old', 'New', 'Location', 'northeastoutside');

grid on;

ylim([0 5]); % Adjust limit to accommodate data range

% Add Value Labels and P-values to the plot

for i = 1:numel(b)

    xtips = b(i).XEndPoints;

    ytips = b(i).YData;

    labels = string(round(b(i).YData, 2));

    text(xtips, ytips, labels, 'HorizontalAlignment', 'center', ...

        'VerticalAlignment', 'bottom');

end

% Optional: Annotate the graph with p-values
```

```
text(1, 4.5, sprintf('p = %.4f', p_static), 'HorizontalAlignment', 'center', 'FontWeight', 'bold');
text(2, 4.5, sprintf('p = %.4f', p_dynamic), 'HorizontalAlignment', 'center', 'FontWeight', 'bold');
```

Matlab script for time until failure:

```
% Time until failure

old_data_failure=[19 24 54 64 46 43 71 80 163 22 41 16 22 21];

new_data_failure=[44 60 70 80 59 70 94 135 181 80 114 63 70 59];

[h1,p1]=ttest(old_data_failure,new_data_failure)

% Time arc

old_data_arc=[37 35 31 50 23 36 42 60 84 25 35 26 31 24];

new_data_arc=[71 50 82 60 70 60 70 93 104 64 72 34 41 50];

[h2,p2]=ttest(old_data_arc,new_data_arc)

figure(1)

% Place the first box at position 1

boxchart(ones(size(old_data_failure)), old_data_failure)
```

```
hold on

% Place the second box at position 2

boxchart(2 * ones(size(new_data_failure)), new_data_failure)

% Clean up the axes

xticks([1 2])

xticklabels({'Past Prototype', 'Current Prototype'})

ylabel('Time Elapsed Until Failure (s)')

title('Static: Time Until Failure for Past and Current Prototypes')

hold off

figure(2)

% Place the first box at position 1

boxchart(ones(size(old_data_arc)), old_data_arc)

hold on
```

```
% Place the second box at position 2

boxchart(2 * ones(size(new_data_arc)), new_data_arc)

% Clean up the axes

xticks([1 2])

xticklabels({'Past Prototype', 'Current Prototype'})

ylabel('Time Elapsed Until Failure (s)')

title('Dynamic: Time Until Failure for Past and Current Prototypes')

hold off
```

Time Until Failure:

Static failure-