Train of Four Monitoring Device

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Abstract

Assessment of neuromuscular blockade during anesthetization is achieved using the Train of Four (TOF) monitoring technique. However, current devices are limited to conditions in which the hand can move freely. The goal of this project was to design, prototype, and test a device which extends the TOF technique to conditions where movement is restricted. Interviews and surveys were conducted with stakeholders and university students to get feedback on preliminary designs. The resulting device consists of a thumb-mounted balloon, which converts the force due to thumb twitches into pressure, which then acts as the physical analog to muscle response. This pressure is transduced and analyzed to produce a TOF count and TOF ratio. A prototype was constructed and tested on human subjects.

1. Introduction

The objective of this project is to design, prototype, and test a unique device that assists medical professionals in monitoring a patient's level of intraoperative neuromuscular blockade in an objective and practical way. During surgery, neuromuscular blocking agents (NMBAs) are administered to temporarily paralyze the patient and allow for endotracheal intubation (Philips, 2011). Monitoring is required throughout the process to ensure that the neuromuscular blockade is sufficient for the surgery to proceed and that it has sufficiently diminished to allow for extubation without residual blockade. One potential issue that physicians need to monitor for is that residual neuromuscular blockade can lead to ICU-acquired weakness and in some cases critical respiratory issues (Sessler, 2004; Kiekkas et al., 2014).

The standard way of quantitatively measuring neuromuscular blockade is called Train-of-Four (TOF). TOF involves the use of a peripheral nerve stimulator (PNS) which provides a TOF electrical impulses to the patient's ulnar nerve through electrodes placed on the skin. These impulses stimulate the nerve, producing a response in the form of a twitch in the muscle. The response of the associated muscle to this stimulus is then measured in two ways:

1. TOF Count: a discrete quantity of twitches (e.g. 2 out of 4 twitches)
2. TOF Ratio: a ratio of the amplitude of the last twitch to that of the first (e.g. 0.8 or 80%)

The TOF Ratio considers the fade caused by a nondepolarizing NMBA. Fade is the decrease in amplitude between the first and final twitches in a TOF. This ratio is a key metric used to determine readiness for extubation and cannot be evaluated without the use of a quantitative measuring device (Sessler, 2004).

Although most anesthesiologists have PNSs, many do not have a quantifiable TOF measuring device, and of those who do, few use it routinely. Instead, they use a series of subjective measurement techniques (Vloka, Hadzic, Shih, Birnbach, 1999). Barriers to use include extensive set up/calibration time, unreliability, a lack of adaptability and economics. Researchers have also noted a confusing user interface in a common measuring device, making human-computer interaction an important barrier to consider (Kopman, 2006). This project will attempt to alleviate these problems.

Axiomatic Design will be used as a framework for the design. Developed by Nahm Suh, Axiomatic Design attempts to treat design as a scientific discipline with universal axioms which apply to all designs (Suh, 2001). We will use strategies developed by Suh (2001), Brown (2011), and Thompson (2013a, 2013b) to structure the design process, choose design solutions for the device and evaluate the design. The decomposition of the design problem and selection of design parameters will be discussed.

Concluding, the purpose of this report is to describe the process of designing, prototyping, and testing of a device that will quantitatively measure the level of neuromuscular blockade in patients and will address limitations present in standard quantifiable TOF measuring devices that are currently on the market.

2. Background

Neuromuscular blockade is monitored in patients to determine the dosage of NMBAs and is measured with the most commonly used method, the TOF. To perform a TOF test, an electrical stimulus is applied to the nerve, which produces a measurable response in the corresponding muscle. However, issues with current devices measuring TOF include precision and repeatability. In the following sections, anesthesia and NMBAs are discussed in terms of monitoring, as well as current devices and human factors that contribute to the dosage of NMBAs administered to patients.

2.1 Anesthesia Types and Applications

The American Society of Anesthesiologists (ASA) sorts anesthesia into three categories including general, regional and local anesthesia. During general anesthesia, a patient is "unconscious and [has] no awareness or other sensations" (American Society of Anesthesiologists, 2018, n.p.). General anesthesia is usually administered for major surgeries. It may be administered through inhalation, or intravenously. Moreover, in regional anesthesia, a doctor injects the anesthetic into a cluster of nerves to numb a large area of the body. There are multiple subclasses of regional anesthesia including spinal and epidural anesthesia. Finally, during local anesthesia, the anesthetic is injected into the tissue to numb a small area of the body. This is usually only for minor surgeries ("Types of Anesthesia", 2018).

2.1.2 *General Anesthesia*

This project focuses on patient monitoring that occurs throughout the general anesthesia process, the only one of the three types in which the patient is unconscious. Doctors consider a patient's health history, prescription medication, and allergies among other factors to determine

the most appropriate medication and dosage for the patient. Before surgery begins, the anesthesiologist administers the anesthesia medication intravenously or through inhalation. After the patient has lost consciousness, the anesthesiologist administers a NMBA to facilitate tracheal intubation, the insertion of a breathing tube into the patient's trachea (Mayo Clinic Staff, 2017). Monitoring the depth of neuromuscular blockade experienced by the patient is important to prevent rejection of the breathing tube and ICU acquired weakness (Sessler, 2004). ICU acquired weakness can manifest as permanent muscle atrophy and temporary limb and respiratory muscle weakness as a result of prolonged exposure to NMBAs, which leads to longer periods of hospitalization (Jolley et al., 2016).

2.2 Neuromuscular Blockade Monitoring

The most common intraoperative monitoring techniques are clinical assessment and TOF monitoring (Viby-Mogensen, 2000). A combination of both of these techniques is recommended (Murray et al., 2017). These techniques are used in determining the correct level of dosage to induce sufficient paralysis for intubation, and the proper time for extubation. Clinical assessment involves the careful examination of patient-ventilator synchrony (i.e., how closely the respiratory muscles of the patient mirror the ventilator’s rhythm; Baumman et al., 2004). When there is little observable dyssynchrony between the patient and their ventilator, the patient is said to be sufficiently dosed with NMBAs (Bouju et al., 2017). TOF monitoring in the dosing stage consists of nerve stimulation and muscle response observation. Nerves are stimulated in a TOF consecutive pulses using a PNS, which applies a current to the patient through electrodes placed on the skin above the nerve to be stimulated. At this stage, muscle response is only quantified as the number of twitches present vs the number of pulses applied (TOF Count). When the TOF

Count reaches one or two for each TOF stimulation, the patient is said to be properly dosed (Bouju et al., 2017).

Monitoring is also needed to ensure proper neuromuscular recovery prior to extubation. Common practice often involves the use of neuromuscular blockade reversal agents which speed the recovery of muscle response (Viby-Mogensen, 2000). Reliable clinical evaluation standards for extubation include: the ability of the patient to sustain leg lift, head lift, or hand grip for five seconds, and maximum inspiratory pressure of greater than or equal to -50 mm of water (Viby-Mogensen, 2000). When a nondepolarizing NMBA is used, a TOF test is recommended to ensure the patient has reached an adequate level of fade to extubate. Fade is the ratio of amplitude of the last twitch in a TOF to the first; this is also known as the TOF ratio.[14] The TOF ratio should be larger than 0.9 prior to extubation (Kopman et al., 2006).

2.2.1 *Nerve Stimulation*

For proper nerve stimulation, the chosen nerve must meet basic criteria such as containing a motor element, being close to the surface, and producing a visible muscle contraction. To achieve nerve stimulation, an electric current is supplied through the skin using electrocardiogram (ECG) electrodes. The PNS is calibrated for each patient using a test performed while the patient is fully conscious. The ideal nerve stimulator should provide controllable, yet constant current since its magnitude affects whether a nerve is activated. The current also should be no greater than 80 mA, as currents above this are unsafe to use. The resistance of a patient's skin is generally between 0 - 5kΩ. Most nerve stimulators supply monophasic, square wave with a period of 0.1 – 0.3 ms because there is no need for a greater time interval than this to produce accurate results. The negative electrode should be placed over the most superficial part of the nerve, while the positive electrode should be placed along the

course of the nerve. For TOF twitch simulation, a frequency of 2Hz with at least 10 seconds between trains is necessary (McGrath, & Hunter, 2006).

2.3 Current Devices

Common objective TOF measuring techniques are categorized by their means of collecting data. Upon stimulation:

- Acceleromyography (AMG) measures the acceleration of a body part, often the thumb.
- Electromyography (EMG) measures the action potential of a muscle upon stimulation.
- Mechanomyography (MMG) measures the force exerted by a muscle.
- Kinemyography (KMG) measures the deflection of a piezoelectric strip attached to the skin at the muscle site.

In a study comparing General Electric's (GE) neuromuscular monitoring devices, the Mechanosensor (KMG) and the Electrosensor (EMG), it was shown that the Mechanosensor overestimated neuromuscular recovery compared to the Electrosensor (Salminen et al., 2016). A field safety notice issued by GE regarding their Electrosensor module suggested that it over indicated the level of neuromuscular blockade which could result in an underdosage of NMBAs (*Urgent field safety notice*, 2015). MMG has been shown to be the most reliable technique, however due to the limitations in mounting and stabilizing the device it has not been used for a commercially available device (Trager et al., 2006). AMG is the simplest technique and allows for less setup and calibration time as well as less expensive designs, however the reliability of AMG has been called into question (McCluskey et al., 1997).

Below is a table summarizing the currently commercially available devices. Advantages are described in terms of each device's competitive advantage compared to other devices on the market. Limitations are regarded with reference to the ideal device.

Table 1: Current Devices (Information From: (Neuromuscular transmission quick guide 2011; Urgent field safety notice 2015; Kopman et al., 2006; Salminen et al., 2016; NMT module product overview, 2012; Stimpod NMS450; Stouffs et al., 2018))

Name	Type	Advantages	Limitations
GE M-NMT MechanoSensor	KMG	• Programmable for hands-off use	• Confusing user interface • Restricted to use on the thumb (abductor pollicis)
GE M-NMT ElectroSensor	EMG	• Programmable for hands-off use	• Extremely noisy output • Confusing user interface • Requires proper placement of five Electrodes • Restricted to use on the thumb (abductor pollicis)
Philips IntelliVue NMT Module	AMG	• Integrated into monitor • Compact design	• Requires range of motion of tested body part • Variability of measurements between tests • Restricted to use on the thumb (abductor pollicis)
Stimpod NMS 450	AMG	• Does not require calibration	• Requires range of motion of tested body part • Restricted to use on the thumb (abductor pollicis)

A clear limitation of all commercially available devices reviewed is lack of adaptability. All of these devices are restricted to use on the abductor pollicis muscle (located in the palm) and all of these devices besides the Electrosensor (EMG), require mobility of the thumb. This limits the use of these devices to operating conditions in which the thumb is free to move for monitoring which is not always the case due to common surgical positioning, described in section 2.4. Some surgeries require that the hand is attached to the body not allowing the anesthesiologist to monitor the movement of the thumb. All of these devices also include a PNS as part of the package. This may be seen as an advantage to some, however most operating rooms already have a PNS and adding a second would simply add to the expense of the device and produce a redundancy (Vloka, Hadzic, Shih, Birnbach, 1999).

2.4 Surgical Positions

Proper patient positioning is an integral part of any surgical procedure. Patients must be positioned in a way that optimizes access to the surgical site. The chosen surgical position must also sustain body alignment, support circulatory and respiratory functions, keep neuromuscular and skin integrity, and allow access to intravenous sites and anesthesia monitoring devices (Rothrock & McEwen, 2018).

The most common surgical position is the supine position (Figure 1) in which the patients lie with their back flat against the bed. In this position, arms are often tucked at the side with palms facing upwards, and the arm may or may not be secured via a strap. Other common positions include the lithotomy, lateral, and prone positions that are shown in Figure 1 (Rothrock & McEwen, 2018).

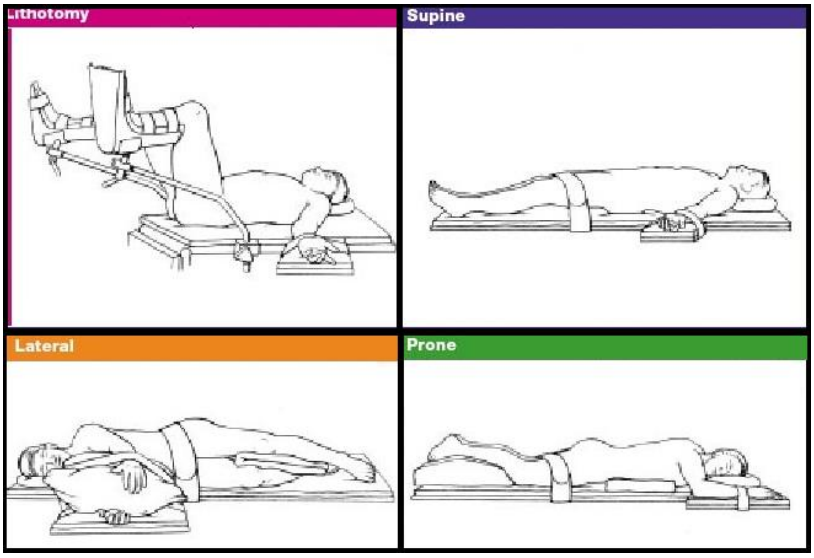


Figure 1: Lithotomy, Supine, Lateral and Prone Surgical Positions (Left to Right, Top to Bottom; Association of Operating Room Nurses, 2005)

As demonstrated by Figure 1, in these surgical positions the palms are facing towards a flat surface or the patient's body, which may not always be conducive to monitoring of the TOF

response. The surgical positioning may inhibit the full range of motion of the thumb. Thus, it is key to build a monitoring device that can capture readings when free movement of the thumb is obstructed.

2.5 Human Factors

The importance of a neuromuscular blockade monitoring device in the operating room stems from the need for medical decisions based on quantifiable information. In anesthesia practice, clinicians need to decide whether to administer a drug antagonistic to NMBAs. The inadequate administration of the antagonistic drug can lead to residual neuromuscular blockade associated with morbidity and death. Research shows that 73% and 71% of clinicians claimed that the two rules that are used most frequently to make that decision are the interval since the last NMBA dose and the patient's breathing pattern, respectively (Videira et al., 2011). When asked, clinicians claimed that significant residual blockade of 5% or higher is more prevalent in the practice of their colleagues (60%) than their own (16%), which makes them overconfident in their ability to estimate the duration of action of intermediate-acting NMBA (Videira et al., 2011). This barrier in implementing experts' recommendations when monitoring neuromuscular blockade can be overcome with the existence of a quantifiable measure (Videira et al., 2011).

Even though the need for a quantifiable measure is prominent, neuromuscular blockade monitoring devices that exist on the market are not operated at all times, often because the devices are not user-friendly and clinicians are uncomfortable using them during surgery. To examine this issue, a case study investigating the human factor in computing systems was conducted. The researchers found people uncomfortable with using an Electronic Remote Blood Issue (ERBI) system designed to remotely issue blood units for transfusion to patients in the operating room (Furniss et al., 2014). Specifically, a research partner said "They have nurses

crying in the corridors too afraid to use the technology in case they make a mistake and too afraid to go back into the room because they will be shouted at." (Furniss et al., 2014). Therefore, designing a user-friendly device is crucial to its successful use.

Understanding the human factors and applying them to the design process will produce an outcome beneficial in terms of minimizing use-related hazards and risks. Unfortunately, medical devices are commonly evaluated when all their parts and properties are specified. By the time the device runs well enough to evaluate, it is too late to change it considerably so applying human factors to the evaluation of the system would not be very effective. However, if the system is tested during the design process when it is still largely hypothetical, there is more room for improvement and for exploring optimization and sensitivity. In a study looking at the user experience of several ventilators, operators had to perform tasks on each of the devices. Results revealed that task-specific processing times differed between the devices. Interface issues also hindered the performance of specific tasks, and usability issues associated with each device decreased the operator's performance while putting the patient's health at risk. However, if human factors were taken into account when designing a device, then this should help eliminate usability issues and improve the efficiency of a device (Spaeth et al., 2017).

Additional research conducted towards understanding the reason that many surgeons decide to reject robotic-assisted surgical techniques found that the main barriers to adoption were perceived ease of use, complexity, usefulness, and behavioral control (BenMessaoud et al., 2011). Some surgeons believe that the traditional practices are adequate to treat patients. Within the perceived ease of use and complexity category, surgeons who use robotic-assisted surgical techniques identified the steep learning curve as a major barrier (BenMessaoud et al., 2011). Even though this research study might have been biased since it was conducted with surgeons

that were using only one type of surgical system, the da Vinci, the experiences of the surgeons show that physicians, and in general healthcare professionals, can often be slow in adopting new technologies (BenMessaoud et al., 2011). Accordingly, applying the human factors to the design process would allow for a user friendly device, could result in less user training, and could reduce the risk of user error (Human Factors and Medical Devices, 2018).

2.6 Summary

A review of the background information revealed the method of monitoring neuromuscular blockade in patients and the devices that are currently on the market which will both be of great use in the design process of our device. The literature review also showed that getting feedback throughout the design process is crucial to developing a user-friendly device. Therefore, we will conduct interviews and surveys with Anesthesiologists and others throughout the design process to receive constructive input on the design and prototype.

3. Interviews with Anesthesiologists

To provide a better understanding of the need for neuromuscular blockade monitoring devices, interviews were conducted with Anesthesiologists. The interviews investigated the criteria that need to be met when designing a device, knowledge about challenges associated with using a neuromuscular blockade monitoring device, and input in initial design concepts.

3.1 Methodology

3.1.1 Participants

Interviews were conducted with five anesthesiologists. Of them, four were male and one was female. All participants provided verbal consent prior to beginning the interview. All participants have been in the field of anesthesiology for more than five years and two of them have been practicing for approximately 30 years.

3.1.2 Design and Procedure

Semi-standardized interviews were conducted to gain an understanding of anesthesiologists' perceptions and experiences with anesthesia devices. The semi-standardized interview format allows the interviewer to develop a set of prepared questions to interview the participants, but also to retain the ability to ask unplanned follow-up questions based on the participants' responses (Berg & Lune, 2012). Topics of the prepared questions included background information on the participant's experience as an anesthesiologist/physician, description of the process of setting up and administering anesthesia, with a focus on the TOF test, and the expectations placed on a device measuring TOF responses. Follow-up questions were asked when a response prompted further inquiry, in order to obtain additional information (Berg & Lune, 2012). Participants were given the list of prepared questions in advance of the

interview to allow them time to think about their responses and to enable a better understanding of the focus of the project. Interviews typically ran between 20 and 30 minutes and were conducted via Skype or conference call. Responses were recorded through note taking. Any personal information was discarded after the analysis of the notes taken to prevent identification of a participant based on their responses. A sample interview guide can be found in Appendix A.

3.2 Results

Responses from the five interviews with anesthesiologists were analyzed to provide insight into the expectations professionals would have for a device measuring TOF, as well as the current reality of performing this test.

3.2.1 Perspectives on Current Measurements Used

Of the participants, 60% believed that the effectiveness of TOF testing is currently limited by a lack of devices that can provide a quantifiable response to the TOF test. In addition to a lack of devices, participants also noted the following limitations to conduction TOF tests: a) limited access to body parts necessary for the current TOF devices to work and b) restricted range of motion of certain areas of the body depending on the type of surgery being conducted. One of the most common restrictions of motion identified was the tucking of the hand to the side of the body underneath a blanket.

While there are a number of limitations to the current methods of measurement, participants consistently reported that being able to quantifiably detect levels of muscle paralysis would offer several advantages to anesthesiologists. The different advantages mentioned by anesthesiologists were: a) elimination of other tests required to assess neuromuscular blockade,

b) greater control over the amount of drugs administered to the patient, and c) more efficient use of surgery time.

3.2.2 Current Device Limitations

While there are several devices currently on the market which can produce quantifiable results from a TOF test, participants identified several challenges with the current selection of devices including cost, reliability, patient discomfort, time, ease of use, versatility, and operational requirements.

Cost plays a major role in the equipment available to the anesthesiologist, as hospitals are private institutions constantly looking for ways to reduce expenses in the face of factors such as increasing Medicare costs and lower birth rates. When asked about it, participants indicated that this has led to a stagnation of progress in the way this test is performed. Of the participants, 60% reported that they use monitoring devices that they estimated to be between 30 to 75 years old because new equipment costs too much. In addition, 60% of the participants recounted that there has been little change in the way that TOF tests have been performed over the course of their careers. When comparing resources available to anesthesiologists, it was discovered that each hospital is equipped differently. Some hospitals provide access to some TOF measuring devices, but other hospitals are greatly lacking in the availability of measurement devices, including relatively basic devices such as electrical stimulators. Thus, we determined from these interview responses that cost is a major consideration for the viability of a TOF measurement device. More specifically, the TOF measurement device needs to be economical, such that a majority of hospitals would consider purchasing it.

From the interviews, issues related to reliability concerns were also expressed with regards to current TOF sensors. Some respondents indicated that cheaper sensors lacked

precision and even those from the same company and model produced noticeable variations between them. These anesthesiologists were concerned with the reliability of the output from these devices. Thus, we discerned from the interviews that an important consideration for a TOF device is reliability, including perceived reliability by the anesthesiologist. If anesthesiologists believe a device is reliable, then this will increase the confidence and trust the anesthesiologist places in the device, and increases the likelihood they will use the device. Consequently, it is important to design a device that produces reliable results.

Patient discomfort was another concern expressed by participants regarding current TOF measurement techniques. Our participants stated that in order to properly calibrate a device, usually a TOF test needs to be performed on the patient prior to the surgery and before they are under anesthesia. This means that the anesthesiologist has the choice between applying shocks to a conscious patient and subjecting them to pain or using the shock values already programmed into the device, which may not be accurate for all patients.

In addition to discomfort, time and ease of use concerns were also expressed by participants. Some of the anesthesiologists we spoke with remarked that some TOF devices are difficult or time consuming to set up. In addition, the anesthesiologists mentioned that performing the TOF test often requires the anesthesiologist to wait five minutes in between subsequent tests to prevent false positive results. Moreover, 60% of participants expressed the desire for the device to be able to be integrated into their current monitors such that the output can be displayed with the rest of the readings. Another feature of interest expressed by participants is the ability for the device to automatically upload and record measurements to a hospital database for more consistent and organized record keeping.

Our interviewees also mentioned that another limiting factor of the current devices was versatility in where the device can be applied to a patient's body. Of the participants, 40% expressed that most of the devices they had used could only be applied to a certain part of the body, usually the thumb and/or eyebrow, and would be useless or of limited effectiveness if used anywhere else.

In addition, participants described limitations of current devices based on operational requirements. For instance, some participants noted that the placement of the device could be difficult or impossible depending on the position the patient needed to be in for the surgery. In addition, participants explained that there is naturally a restriction of movement caused by common surgical positions. Participants also noted that the use of sensing elements utilizing kinemyography and accelerometry could be problematic due to potential restrictions of movement in scenarios where the body part is hidden or obstructed by blankets. Other limitations of the device include the placement of other surgical equipment such as IV tubes and sensors, which the device must not interfere with.

3.3 Summary

The interviews with the anesthesiologists allowed us to identify the need for a quantifiable TOF device as well as key factors that we should consider when designing our prototype. Specifically, developing a cost-effective device is crucial to the integration of the device in the hospital. This could be achieved by making sure that the components used to create the device are not very expensive. To account for the reliability concern, a test will be performed at least twice with participants to ensure that the device works properly and gives the same result both times. Therefore, these tests will account for both within-participants and in-between-participants reliability. Another consideration is time and ease of use which will be addressed by

testing our device and identifying the time it takes and the difficulty to set it up. Lastly, to account for the operational requirements, the mounting system will hold the hand stable in a fist position so that it doesn't move during surgery, will be easy to put on, and will leave the back of the hand open for other surgical equipment necessary for the surgery. These considerations are integrated in the design process that follows in the next section.

4. Design

The device will be designed using Axiomatic Design. Axiomatic Design was developed in the 1980s by Nam Suh and attempts to approach design as a science. Since then, it has been further developed in industry and academia. Many of these developments will be used in this methodology. Axiomatic Design can be described as having three basic elements: design axioms, structures and processes as shown in Table 2 (Brown 2005). The design axioms are universal laws to which all good designs must adhere. They are:

Axiom 1: Maintain the independence of the Functional Requirements, and

Axiom 2: Minimize the information content of the design

These axioms are the core of Axiomatic Design, however in order to accurately apply them, structures and processes are also necessary. The three basic elements of Axiomatic Design are described in the table below and will be discussed further in relevant sections of this methodology.

Table 2. Basic Elements of Axiomatic Design (Brown, 2005).

Elements	Components	Details	Notes
Axioms	Maintain Independence	Decouple functional elements	Provides adjustability and controllability
	Minimize Information	Maximize probability of success	Provides robustness and high yield
Structures	Lateral	Design domains	Customer-Functional-Physical-Process
	Vertical	Hierarchies in the domains	Decomposition from general to specific
Processes	Zig-zagging decomposition	Between functional and physical domains	Generation of vertical hierarchies
	Physical integration	Recomposition	Construction into physical systems

4.1 Need Identification

Axiomatic Design begins in the Customer Domain with the development of Customer Needs (CNs). It is important to note that CNs need not be solely functional in nature, but can become Functional Requirements (FRs), Non-Functional Requirements (nFRs), Constraints (Cs), Selection Criteria (SC), and Optimization Criteria (OC) (Thompson, 2013b). The identification of CNs was carried out through research of recent journal articles and current commercial TOF devices demonstrating drawbacks and factors needing improvement, as well as interviews conducted with Anesthesiologists.

4.1.1 *Functional Requirements and Design Parameters*

As described by Suh, FRs define what a design must do (i.e., its functions). In order to properly implement the design axioms, careful consideration must be taken when determining

FRs to avoid confusion with other requirements. After defining Customer Needs, they were categorized into FRs, nFRs, Cs, SCs and OCs, and the top-level functional requirement (FR0) was developed. FR0 of this project was defined as: Measure, relay and display real-time muscle response information during stimulation. The top-level design parameter (DP0; i.e., the design solution to the functional problem defined by FR0) is: Real-time muscle response measuring device.

After defining the top-level of the design in the functional and physical domains, a decomposition was needed. The basic criteria of FR decomposition are that it is Collectively Exhaustive and Mutually Exclusive (CEME; Brown, 2011). In other words, the sum of the FRs at one level of the hierarchy must equal the parent FR at the level above and there must be no overlap between FRs at the same level under the same parent. Violating these decomposition criteria would result in a violation of Axiom 1 because it would then result in coupling between FRs as described by Brown (2006). In order to achieve a CEME decomposition, Brown suggests the use of a theme in guiding the decomposition (Brown, 2011). In this design, the theme for the top-level decomposition was the converting between forms of energy. Ultimately, the device will digitally display a physical input. Thus, the three conversions which need to be made are between the physical input and an electrical output (FR1), the electrical output and an inputtable form for the monitor (FR2), and the input of the monitor to a usable visual output (FR3). Shown below is a flow chart showing the top-level design decomposition. The arrows denote the order in which the decomposition took place. The top-level design parameters (DP1-3) have not yet been chosen as they required further research into measurement techniques, data transfer and conversion systems, and understanding of interface needs. The top level design decomposition is shown in Figure 2.

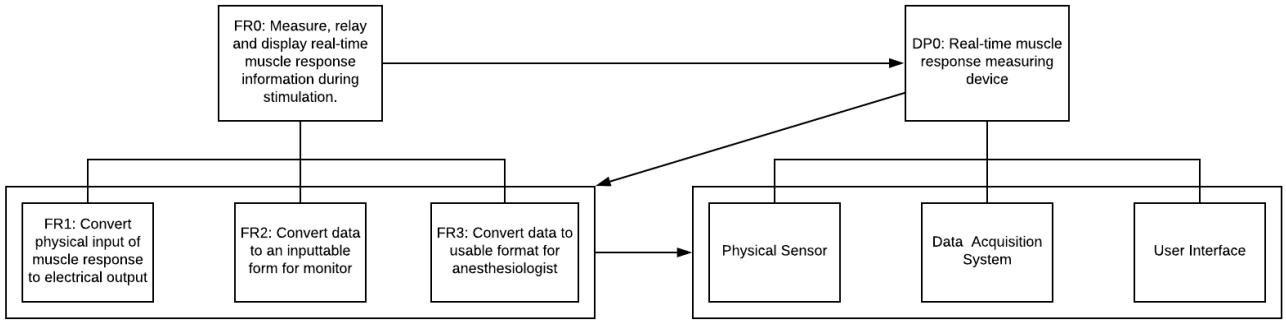


Figure 2. Top Level Design Decomposition, including Functional Requirements (FRs) and Design Parameters (DPs)

4.1.2 *Constraints, Optimization, and Non-Functional Requirements*

In the Need Identification process, Customer Needs (CNs) were identified which did not fall under the definition of FRs, such as ease of use. These CNs were categorized as either non-Functional Requirements (nFRs), Constraints, Selection Criteria, or Optimization Criteria as described by Thompson (Thompson, 2013b). Non-Functional Requirements define how a physical artifact should be, rather than what it should do. Constraints define a limit of a certain aspect of a design, such as cost or weight, and require a hard value (e.g., the device must cost under $200 to manufacture). Selection Criteria determine which design to choose when more than one possible design can fulfill the FRs, nFRs, Constraints and adhere to the axioms (e.g., choose the lightest design). Optimization Criteria define what aspects of the design should be optimized. SCs and OCs are often specified in rank order.

Table 3. Categorized Needs

Constraints	Non Functional Requirement	Optimization Criteria (in order of importance)	Selection Criteria (in order of importance)
Cost	Sterilizability	Quantifiability	Ease of Use/Set up
		Repeatability/Precision	Versatility
FDA Regulations	Novelty	Reliability	Patient comfort
		Integrability	Renewability

The cost to hospitals restricts devices that are new to the market and in clinical trial. The hospitals will receive a reimbursement each time they use the device, which incentivises their use. The Current Procedural Code (CPT) code will be used to determine the rebate Medicare gives to the hospital after the use of the device. The current devices that are used for TOF monitoring produce a reimbursement of roughly $320 (Centers for Medicare and Medicaid Services, 2016).

4.1.3 *Analysis*

Each Design Parameter selection will be evaluated according to the axioms. Axiom 1 will be evaluated using Design Matrices as described by Brown (2006). Design Matrices address the relationships between FRs and DPs and determine if there is coupling between them (i.e., if one DP affects more than one FR). These Design Matrices will be built using Acclaro software ("Acclaro DFSS," n.d.). The presence of a relationship between an FR and a DP is denoted by an X, and the lack thereof by a 0. Shown below is the expected design matrix for the top level of the design.

Table 4. Top Level Design Matrix

	DP1: Physical Sensor	DP2: Data Acquisition System	DP3: User Interface
FR1: Convert physical input of muscle response to electrical output	X	0	0
FR2: Convert data to inputtable form for monitor	X	X	X
FR3: Convert data to usable format for anesthesiologist	X	0	X

Ideally, the matrix would be diagonal (i.e., all FRs would only be affected by their corresponding DPs). However, it is expected that because the nature of the electrical signal generated by DP1 determines the data conversion (DP2) necessary to satisfy FR2 and some normalization component of the displayed output of DP3, there will be coupling. Fortunately, if rearranged (FR-DP pair 2 is switched with pair 3) this can form a lower triangular matrix (i.e., the coupled FR-DP pairs all occur on one side of the diagonal, see Table 5), Axiom 1 can still be preserved with the appropriate order of adjustment. As long as DP1 is designed before DP2 is designed, and DP3 is designed before DP2 is designed, the FRs will remain uncoupled.

Table 5. Top Level Design Matrix Rearranged

	DP1: Physical Sensor	DP2: User Interface	DP3: Data Acquisition System
FR1: Convert physical input of muscle response to electrical output	X	0	0
FR2: Convert data to usable format for anesthesiologist	X	X	0
FR3: Convert data to inputtable form for monitor	X	X	X

Axiom 2 will be used in cases where two or more designs satisfy Axiom 1. Adherence to Axiom 2 will be determined by calculating the information content (I) according to the equation below for each design and choosing the design with the lowest information content. Probability of success is calculated by dividing the common range by the system range as shown in the equation shown below. The common range is defined as the intersection of the design range (the range of DP values which would satisfy the FR) and the system range (the range of DP values achievable). Note: this calculation is only possible with quantifiable DPs, or FRs with quantifiable metrics.

$$p = \frac{Common\ Range}{System\ Range}; I = log(\frac{1}{p})$$

4.1.4 *Results- Overall Design*

Because none of the common objective TOF measuring techniques are usable with immobile hands, a new technique was developed. This technique requires the capture of limited movement of the thumb when the hands are strapped in suboptimal locations. It also requires the capture of varying motion along multiple axes. Thus, the physical interface must capture small,

multidirectional displacements of the thumb. The solution we developed for this problem was a variation on a bulb-pump. The physical output will be a pressure produced by the deflection of a flexible balloon closed at one end with tubing attached to the other. The pressure will then, be transmitted through the tubing where it will reach a pressure transducer, which will convert the pressure to an electrical potential. This allows for the measurement of very small movements.

In order to capture movement in multiple axes, the combination of the shape of the balloon and the resting position of the thumb (dictated by the mounting system) should make possible movements of the thumb produce a force on the balloon which is normal to its surface. This would allow proper transmission of pressure through the balloon. Another important aspect of the design is that the balloon must be constrained such that the force of the thumb on the balloon results in pressure transmission rather than displacement of the balloon. Thus, a decomposition of FR1 (Convert physical input of muscle response to electrical output) is shown below.

Table 6. FR1 Decomposition

FR1.1: Produce pressure upon displacement of thumb	DP1.1: Balloon
FR1.2: Maintain desired component positioning	DP1.2: Mounting System
FR1.3: Convert pressure to electric potential	DP1.3: Pressure Transducer

The design was then evaluated for adherence to Axiom 1. The only existent coupling (as shown in the design matrix below) was found between the balloon (DP1.1) and maintaining the desired component positioning (FR1.2) because the shape of the balloon would affect how it can be held in place. Thus, we have a lower triangular matrix which can be solved by adjusting DP1.1 before DP1.2. Therefore, DP1.1 should be designed before DP1.2, however DP1.3 can be solved independently as it is uncoupled from DP1.1 and DP1.2.

Table 7. Design Matrix FR1 Decomposition

	DP1.1: balloon	DP1.2: Mounting System	DP1.3: Pressure Transducer
FR1.1: Produce pressure upon displacement of thumb	X	0	0
FR1.2: Maintain desired component positioning	X	X	0
And FR1.3: Convert pressure to electric potential	X	0	X

The design of DP1.1 was then evaluated according to Axiom 2. In order to minimize information, the balloon should capture as many directions of movement as possible. The greater the overlap of directions of force in which the balloon would create a pressure and the range of directions possible for the thumb during a twitch, the higher the probability of success. It is also important that the direction of force does not dictate the magnitude of pressure (i.e., the pressure created in the balloon should be independent of the direction of displacement).

4.2 Balloon Optimization

4.2.1 *Simple Analytical Model*

When we first tested our system, we obtained pressure readings of 0.1-0.2 psi. These pressures were almost indistinguishable from noise of any low-cost sensor. Due to limitations in the sensitivity and precision of pressure transducers, the change in pressure created using the proposed device must be optimized. This optimization requires a greater understanding of the

physics involved in the deformation of and subsequent pressure created by the balloon. To provide a cursory understanding of the relationships between geometric parameters and pressure output, a simple two-dimensional model was developed. The model was based on Hertzian contact, and adiabatic compression of an ideal gas.

Hertzian contact is an analytical method which determines stresses on bodies in contact. The solutions rely on the following assumptions (Ugural & Fenster, 2011):

1. The contacting bodies are isotropic and elastic
2. The contact areas are essentially flat and small relative to the radii of curvature of the undeformed bodies in the vicinity of the interface.
3. The contacting bodies are perfectly smooth, and therefore only normal pressures are taken into account.

The bodies in question can be considered elastic, and smooth, but are not isotropic radially. They are, however, isotropic in the circumferential direction. The second assumption is not valid due to the large deformation of the balloon. Hertzian stresses are, therefore, not an accurate model of the system, but can provide relationships between parameters and outputs e.g., the relationship may be that pressure decreases quadratically with radius, and Hertz gives a linear relationship, however we gain an understanding that increased radius leads to decreased pressure.

Hertzian analysis was carried out for a spherical surface assumed to be in contact with a flat surface (spherical surface was chosen due to the limitations of Hertzian contact analysis in obtaining the deflection of cylindrical contact with flat surfaces). The following equations were used (Ugural & Fenster, 2011):

$$a = 0.880\sqrt[3]{Fr\Delta} \quad (1)$$

$$\delta = 0.775 \sqrt[3]{\frac{F^2 \Delta^2}{r}} \quad (2)$$

Where: a is the radius of contact, r is the radius of the sphere, F is the applied force, δ is the deflection of the sphere, and:

$$\Delta = \frac{1}{E_1} + \frac{1}{E_2}$$

Where E_1, and E_2 are the elastic modulus of the sphere and flat surface respectively. The modulus of the sphere was taken as the bulk modulus of the entire balloon. As obtained by Hall, the bulk modulus of a fluid filled spherical shell is (Hall, 1974):

$$k_b = f + \frac{\left(\frac{4t}{3b}\right) g(1+\nu)}{1-\nu} \quad (3)$$

where f is the fluid bulk modulus, g is the shear modulus of the solid (walls), and ν is the Poisson's ratio of the solid. Then we have:

$$E = 3k_b(1-2\nu) \quad (4)$$

Using these results, the simple model assumed that the sphere was deflected instantaneously by the applied force to a deformed state which, for the sake of simplicity, was modeled as a sphere with a cap of height, δ, removed. Therefore, the change in volume was found to be:

$$\Delta V = \frac{\pi}{3}[\delta^2(3r-\delta)] \quad (5)$$

The process was assumed adiabatic, thus the change in pressure due to the initial deformation was obtained as:

$$\Delta P = \left\{\left[\frac{V_1}{V_1 + \Delta V}\right]^{\gamma} - 1\right\} P_1 \quad (6)$$

where the heat capacity ratio is defined as:

$$\gamma = \frac{C_p}{C_v}$$

The balloon was then assumed a sphere of volume $V_1+\Delta V$. The pressure change was then modeled to instantaneously create a dilation of the sphere as described by Mukherjee (Mukherjee, 2017):

$$\delta = \frac{\Delta P r^2}{2hE}(1-\nu) \quad (7)$$

$$\Delta V = \frac{4\pi}{3}[(r+\delta)^3 - r^3] \quad (8)$$

Finally, a final change in pressure was obtained using equation 6. The results can be found in Figure 3. For each parameter, if the domain is large enough, the model predicts an optimal value can be chosen to maximize the pressure. If a custom balloon were to be designed and manufactured, these optimal parameters would be chosen. The accurate determination of these parameters was of interest and led to the development of a more complex model.

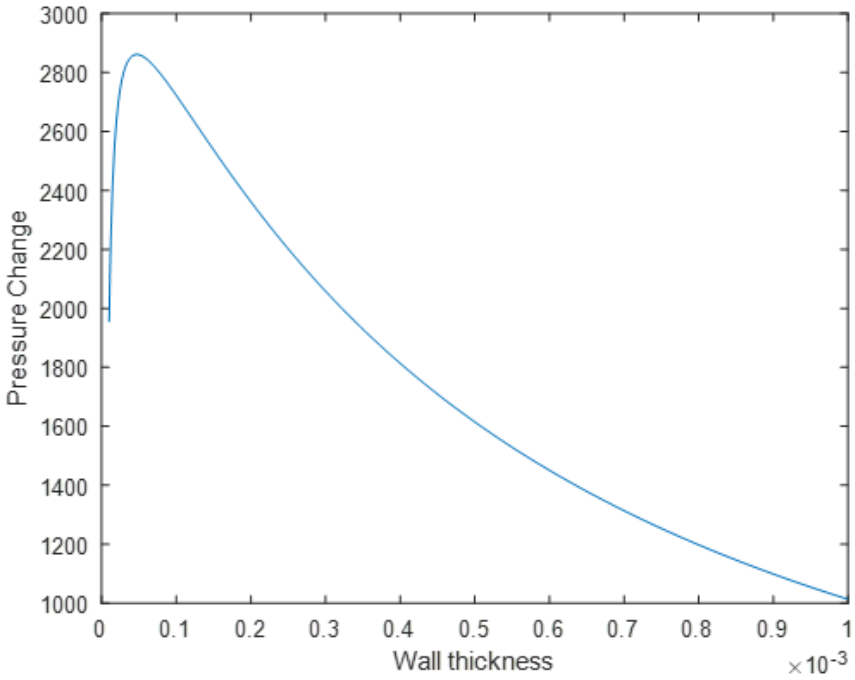


Figure 3. Relation Between Wall Thickness and Pressure Change

4.2.2 *Numerical Model*

This model would be useful in the optimization of the design of the balloon. In order to optimize the balloon, a customized balloon would be necessary. Thus, the model would be run with varying parameters through the range of values possible in manufacturing and fit to the overall design. Due to time and resource constraints, this level of optimization was not carried out.

This more complex model was created using COMSOL Multiphysics. A 2-D axisymmetric model (depicted in Figure 4) was created which considered the effects of internal pressure on the expansion of the balloon as the balloon was compressed. The process was considered adiabatic. The internal volume of the half sphere in the model was determined by multiplying the integrated surface area by the ratio of volume to surface area in the undeformed

state. This simplification was necessary because the mesh could not be made fine enough (without making the model too computationally expensive) to normalize the initial pressure when using a surface integral for the volume. The plates in contact with the balloon were ramped through a prescribed displacement and the resultant contact force was post processed. Thus, the pressure change due to a particular force applied by the thumb can be measured and compared across designs.

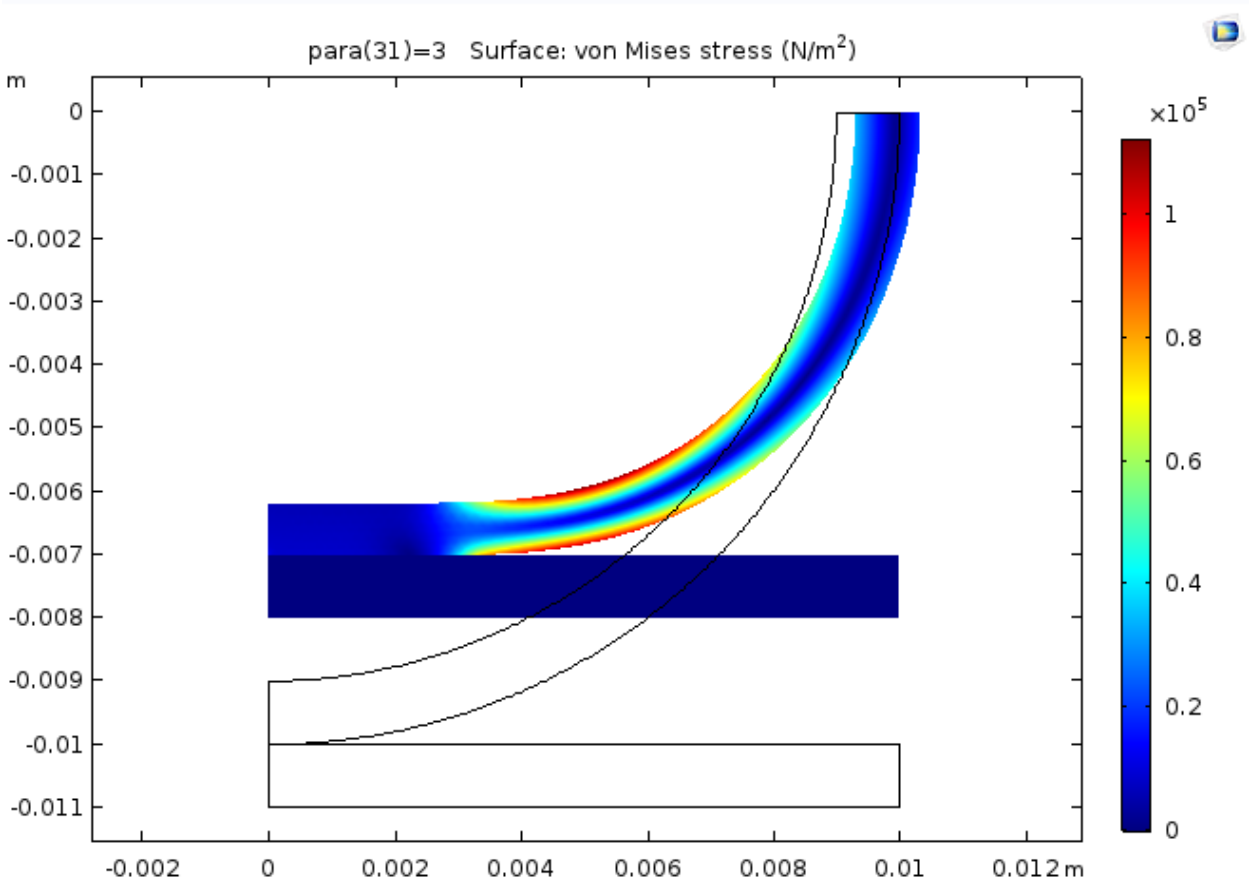


Figure 4: 2-D Axisymmetric Model of Plate-Balloon Interaction with 3 mm Displacement

The figure below shows the produced pressure for balloons of various radii. In this example, the minimum radius allowed by the design was 10 mm due to worries of bottoming out (crushing the balloon until both plates are touching) with smaller radii. This constraint would

change based on material and wall thickness. In this case, the smallest radius allowed is the optimal choice. In practice, more variations would be studied to fully optimize the system.

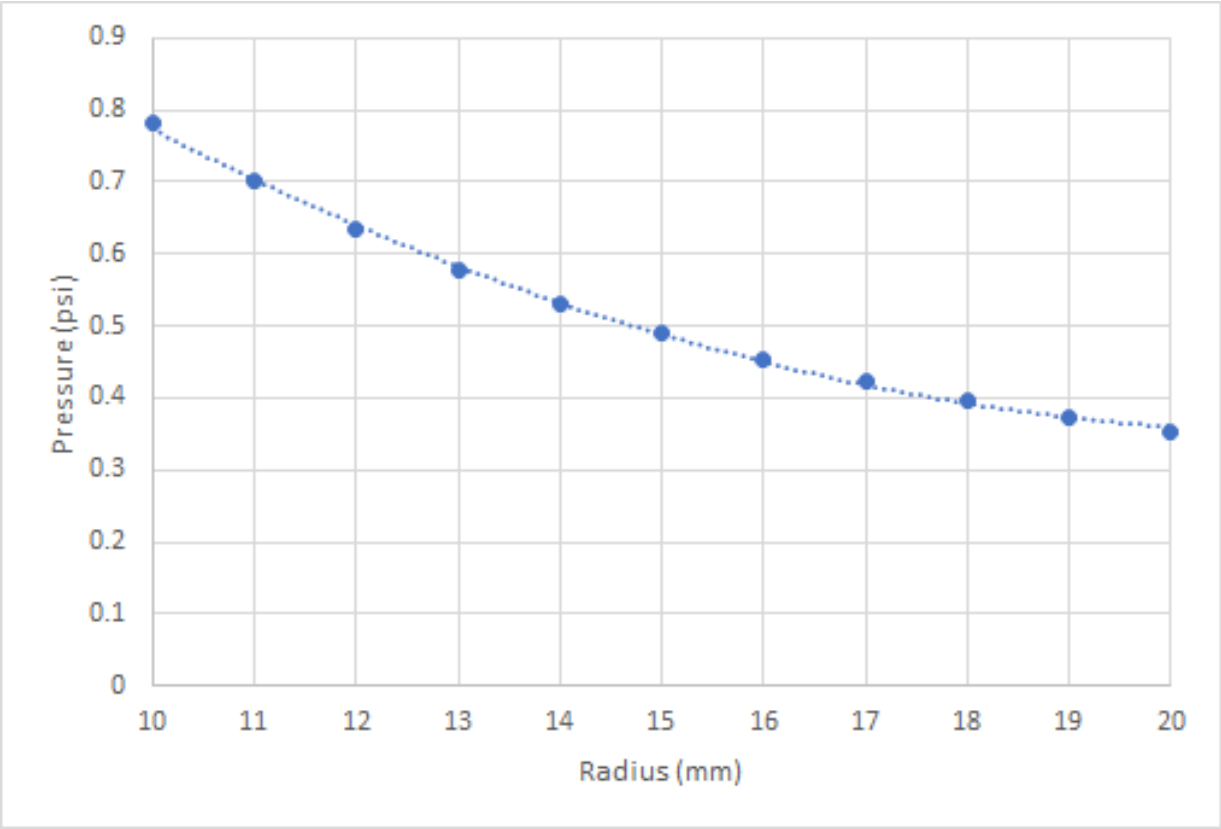


Figure 5: Example Graph of Radius vs Pressure

4.3 Balloon Mounting System Optimization

4.3.1 *Plate Design*

Because the sensitivity of the device is determined by its ability to convert an input force from the thumb into a change in pressure in the balloon, it is crucial that the plates between which the balloon rests are kept in alignment with each other. This alignment was maintained by

an elastic strap which served to provide a restoring spring force when the plates were misaligned horizontally, and kept the plates in contact with the balloon at all times.

4.3.2 *Plate Placement*

From a biomechanics standpoint, we are looking to maximize the moment of the thumb around the joint which is quantified as the cross product of the distance and the force of the thumb twitch. With a larger distance vector, the moment created is also larger which allows for a larger force being translated into the balloon. Thus, the thumb should have the greatest distance possible to the balloon and the tip of the thumb should strike the balloon. This would occur at the proximal phalanx for the most natural twitch motion.

4.4 Pressure Sensor

A tube connects the balloon to an analog pressure sensor, in order to measure the pressure generated by depressing the balloon. Our preliminary tests showed that pressure variations generated during the train of four tests generally ranged between 0.2 - 2 psig, using our prototype. Therefore, we selected a sensor that would be appropriate for this range. The chosen pressure sensor for the prototype is the Honeywell HSC TruStability® Analog Pressure sensor (HSCSAND005PGAA5). This pressure sensor has a range of 0 - 5 psig, and an accuracy of ± 0.0125 psi, making it sensitive enough to record subtle variations in the pressure generated during a train of four test. Pressure values are updated at approximately 1 kHz for this sensor (Honeywell, TruStability Pressure Sensors, 2014). The sensor is calibrated to work between 0 °C and 50 °C and can be used with dry gases such as air (Honeywell, TruStability Pressure Sensors, 2014).

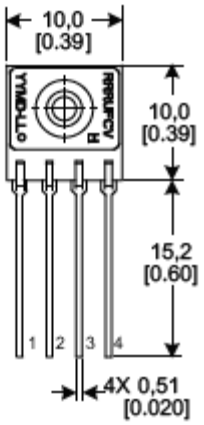


Figure 6: Sensor Pin layout

(Honeywell, TruStability Pressure Sensors, 2014)

As shown in Figure 8, the sensor contains 4 pins. Pin 1 has no connection, pin 2 is a 5.0 V constant DC voltage supply (V_S), pin 3 is the output analog voltage from the sensor (V_{OUT}), and pin 4 the ground (V_{GND}). The sensor pressure output is governed by the following linear equation:

$$P_{applied} = \frac{(V_{OUT} - 0.10\,V_S)(P_{max} - P_{min})}{0.8\,V_S}$$; where

P_{max} - P_{min}= 5 psi (the range of the sensor),

$P_{applied}$ = the output pressure of the sensor in psig

(Honeywell, TruStability Pressure Sensors, 2014).

When the known variables are plugged in the equation works out to be:

$$P_{applied} = \frac{V_{OUT} - 0.5}{0.8}$$ psig

4.5 Sensor Mounting System

The mounting system underwent multiple iterations with the main focal points being low cost, versatility, ease of use, and consistency in data reading. Categories for grading each design were decided on and weighted as a group using axiomatic design parameters. Each design was discussed and graded until the group decided on four preliminary designs, shown in Figure 9. A survey, which can be found in Appendix B, was developed for getting feedback on the four preliminary designs.

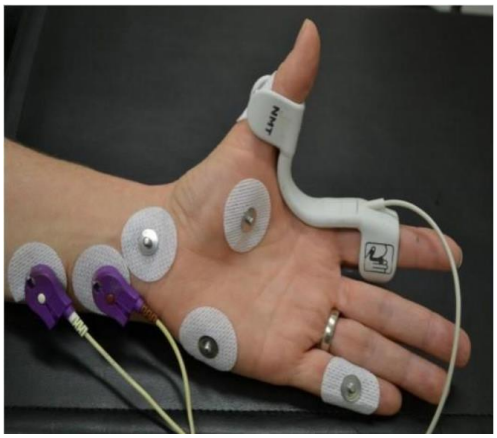
	
“Thumb and Wrist Sleeve” Design (Robby’s Thumb Saver, n.d.)	“Thumb Sleeve” Design (Evo Shield Thumb Guard, n.d.)
	
“Thumb and Index Finger Straps” Design (Kinemyography - Adductor Pollicis DSC_0016, n.d.)	“Band Aid” Design (Finger TPS | PPS, n.d.)

Figure 7: Preliminary Designs

4.5.1 *Survey Methodology*

The survey was conducted with 60 participants enrolled in a university in the New England area of the United States. Of the participants, 28 were female, 30 were male, and 2 did not specify. The survey was administered online, and participants were given an informed consent form electronically. After providing informed consent, participants viewed each of the four preliminary designs one at a time. The designs were shown in a random order, so each participant saw the designs in a randomized order. This was done so that the order of presentation could not influence responses. After viewing each design, participants answered three questions regarding the design. Participants ranked each design based on ease of use and possibility of setting up on a scale from 1 (very easy) to 5 (very difficult). After viewing all four designs, participants ranked-ordered their preferred designs.

4.5.2 *Survey Results*

Since this survey utilized a within-participants design, repeated-measures ANOVAs were performed using the IBM SPSS Statistics Program. The type of rating (e.g., ease of use) was the dependent variable and the within-factors were each of the designs. There were no between-participants factors for these analyses. When a significant interaction emerged, a T-Test was performed to determine the differences between the designs.

Ease of Use

Participants rated each design based on its perceived ease of use. The repeated measures ANOVA showed a statistically significant interaction between the ease of use rating and the four designs, F (3, 57)=66.02, $p < .001$, η_p^2=.53). Since there was a significant interaction, within-participant t-tests were conducted to further investigate how each design compared with one another. The “Thumb and Wrist Sleeve” (M=1.73; SD=.78) was perceived to be easier to use

than the “Thumb and Index Finger Straps” (*M*=3.27; *SD*=1.13) design, *t*(59)=-10.27, p< .001. The “Thumb and Wrist Sleeve” (*M*=1.73; *SD* =.78) was also perceived to be easier to use than the “Band Aid” (*M*=3.27; *SD*=.88) design *t*(59)=-9.23, p<.001. Additionally, the “Thumb Sleeve” (*M*=1.75; *SD*=.82) was perceived to be easier to use than the “Thumb and Index Finger Straps” (*M*=3.27; *SD*=1.13) design *t*(59)=-9.16, p<.001. Finally, the “Thumb Sleeve” (*M*=1.75; *SD*=.82) was perceived to be easier to use than the “Band Aid” (*M*=3.27; *SD*=.88) design *t*(59)=-11.56, p<.001. The results are shown in Figure 10.

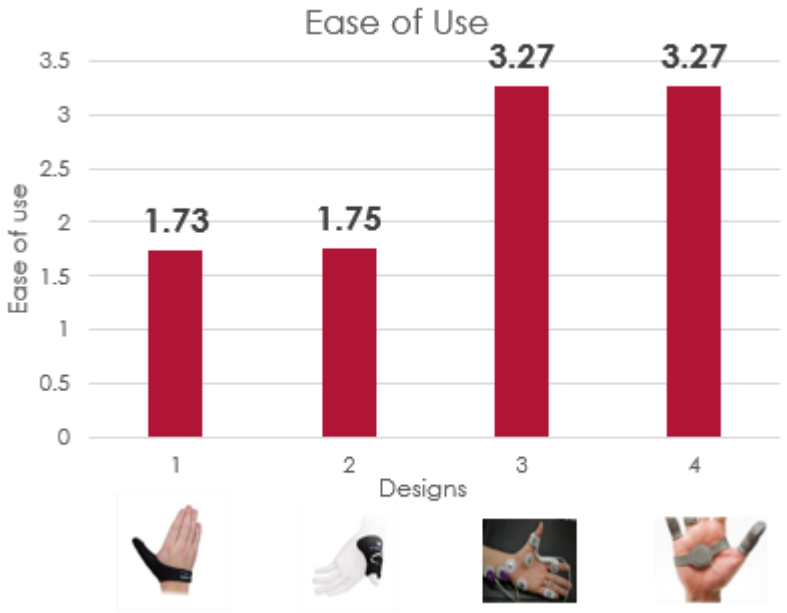


Figure 8: Designs Ranked Based on Ease of Use

Possibility of Setting Up Device

Participants also indicated how possible they perceived the device would be to set up for each design. A repeated measures ANOVA showed a statistically significant interaction between difficulty setting up and the four designs, F (3, 57) = 22.04, p < .001, η_p^2= .27. To better

understand how each design was perceived, within-participants t-tests were conducted. The "Thumb and Wrist Sleeve" (*M*=1.90; *SD*=.82) was perceived to be easier to set up than the "Thumb and Index Finger Straps" (*M*=2.67; *SD*=.95) design, *t*(59)=-5.02, p< .001. The "Thumb and Wrist Sleeve" (*M*=1.90; *SD*=.82) was also perceived to be easier to set up than the "Band Aid" (*M*=2.47; *SD*=.91) design *t*(59)=-3.85, p<.001. Furthermore, the "Thumb Sleeve" (*M*=1.70; *SD*=.67) was perceived to be easier to set up than the "Thumb and Index Finger Straps" (*M*=2.67; *SD*=.95) design *t*(59)=-6.69, p<.001. Finally, the "Thumb Sleeve" (*M*=1.70; *SD*=.67) was perceived to be easier to set up than the "Band Aid" (*M*=2.47; *SD*=.91) design *t*(59) =-4.96, p<.001. The results are shown in Figure 11.

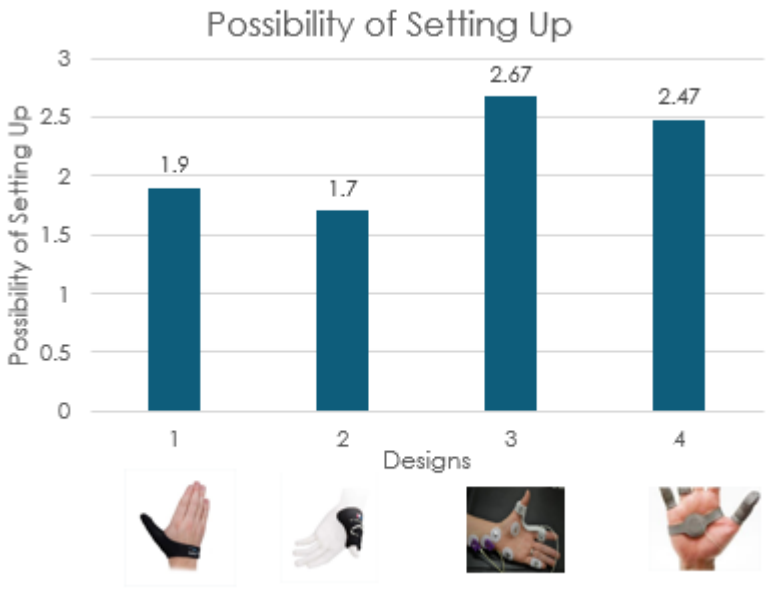


Figure 9: Designs Ranked Based on Possibility of Setting Up Properly

Ranking

The participants ranked the designs in order of preference. A repeated measures ANOVA showed a statistically significant interaction between ranking and the four designs, F (3, 53) = 13.94, p < .001, η_p^2= .20. Within-participant t-tests were conducted to further investigate how

each design compared with one another. The “Thumb and Wrist Sleeve” (*M*=2.02; *SD*=1.07) was ranked higher than the “Thumb and Index Finger Straps” (*M*=3.34; *SD*=.90) design, *t*(55)=-6.11, p< .001. Furthermore, the “Thumb Sleeve” (*M*=2.25; *SD*=.94) was ranked higher than the “Thumb and Index Finger Straps” (*M*=3.34; *SD*=.90) design *t*(55)=-5.46, p<.001. Finally, the “Band Aid” (*M*=2.39; *SD*=1.11) was ranked higher than the “Thumb and Index Finger Straps” (*M*=3.34; *SD*=.90) design *t*(55) =4.52, p<.001. The results are shown in Figure 12.

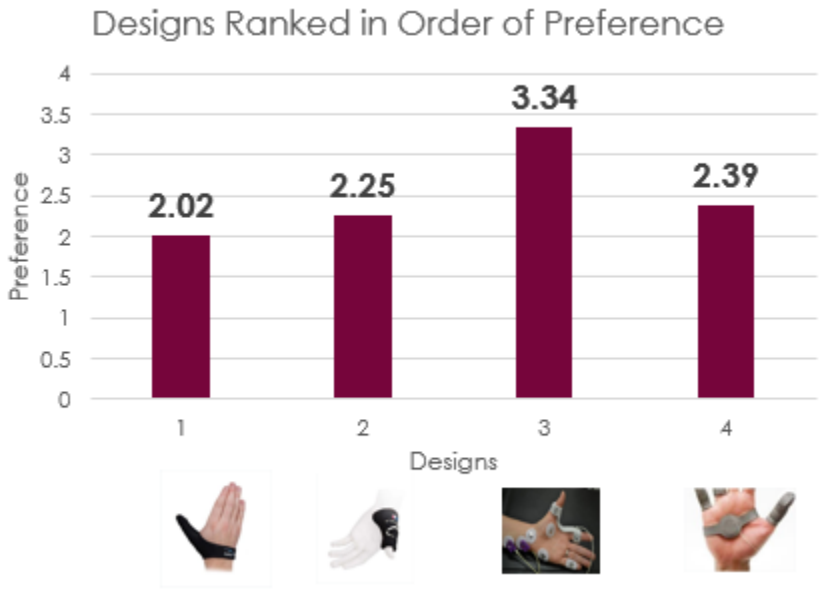


Figure 10: Designs Ranked in Order of Preference

4.5.3 *Survey Discussion and Summary*

Overall, the results from the survey indicated that the “Thumb and Wrist Sleeve” and “Thumb Sleeve” designs were evaluated more positively than the other two (“Thumb and Index Finger Straps” and “Band Aid”) designs. These two designs were also ranked as the top two designs by both the human participants as well as the anesthesiologists. This makes sense because these two designs were very similar in nature. Since the non-medical participants and the anesthesiologists preferred the “Thumb and Wrist Sleeve design”, we chose to develop the

prototype for this particular design. However, while the anesthesiologists preferred this design they did express concerns of using the device if the arms were tucked. Therefore, we kept this concern and possible limitation in mind when developing the prototype.

4.6 Manufacturability and Sustainability

The simplicity of our design allows for easy manufacturability and low costs. Using removable parts makes the assembly and set up smooth and the cleaning easy. While devices of this nature that are on the market usually include a TOF muscle stimulator which raises the total cost significantly, most hospitals have access to these devices separately, allowing us to reduce costs by not including a redundant feature. By 3D printing the plates and using balloons that are already a staple to the medical community, the overall manufacturing is reduced to the mitten, sensor housing, and data acquisition housing. The housings for the sensor and DAQ box are made from PLA, a low cost and easily workable polymer, and the mitten is made from a 70% composite bamboo fabric, which is both hypoallergenic and more environmentally friendly than other common fabrics.

4.7 Engineering Standard Application

The engineering standard being being partially applied to the design of this TOF device is ISO 13485:2016. This is an internationally recognized quality standard which states the requirements of the Quality Management System (QMS) for the design and manufacture of medical devices throughout the world. The 2016 version of this standard expands the profile of organizations to which the standard may apply, in this case including the design, development and production of a medical device. Many jurisdictions require certification in this standard before the sale of medical devices is allowed. The requirement sections 1-8 of the standard are

as follows: “Scope”, “Normative Reference”, “Terms and Definitions”, “General Requirements”, “Management” “Responsibility”, “Resource Management”, “Product Realization”, and lastly, “Measurement, Analysis, & Improvement”. To view the details and comparison of ISO 13485:2016, a license is required; overview information is available at (ISO 13485:2016 Requirements).

4.8 Economic, Environmental, and Societal Impact

The TOF monitoring device would have a minor economic impact on hospitals since it would be cost effective saving hospitals valuable resources. Currently, there is no discernable environmental impact except from manufacturing; the device in question requires minimal resources compared to many other medical devices, with the bulk of it being made from biodegradable, recyclable, or reusable material. A positive societal impact would be reducing hospital stay since it would allow a quicker and safer reversal of neuromuscular blockade; in general, the device would reduce the risk of surgical procedures for patients.

5. Prototype and Testing

5.1 Data Acquisition System

The data acquisition system (DAQ Box) consists of an Arduino Uno R3 which is connected to the Honeywell Analog Pressure Sensor (HSCSAND005PGAA5), described earlier. The Arduino gives us a cost effective way to collect data from an analog pressure sensor and has a theoretical sampling frequency of 10kHz. As mentioned earlier, the sensor has a sampling rate of 1kHz, our theoretical sampling rate. In practice, we were only able to achieve an average of 12 Hz due to limitations in our script, and the processing power of the Arduino. This can be improved by using a more powerful DAQ Box or by further optimization of the governing code.

As shown in Figure 13a, the Arduino and a mini-breadboard are housed in a 3D printed PLA housing. The housing allows access to the USB cables that connect to a PC. The housing also exposes the stop button which protrudes from the breadboard. When pressed, the stop button indicates to the code, that train of four data collection has stopped. A red LED indicator light also protrudes from the housing, which lights up while the system is collecting train of four data, and turns off when the button is pressed and data collection has stopped. Finally, the housing contains a hole for the cable that connects the Arduino to the sensor. The sleeved cable contains the three wires which connect to the honeywell pressure sensor as shown in Figure 13b.

Figure 13b, shows the sensor housing which is strapped to the patient's hand, by a velcro strap. The reason that the pressure sensor is separated from the Arduino is to minimize the volume of pressure tubing needed in the system. When minimized, the pressure variation caused by depressing the balloon, is maximized, as discussed in section 4.1.6.

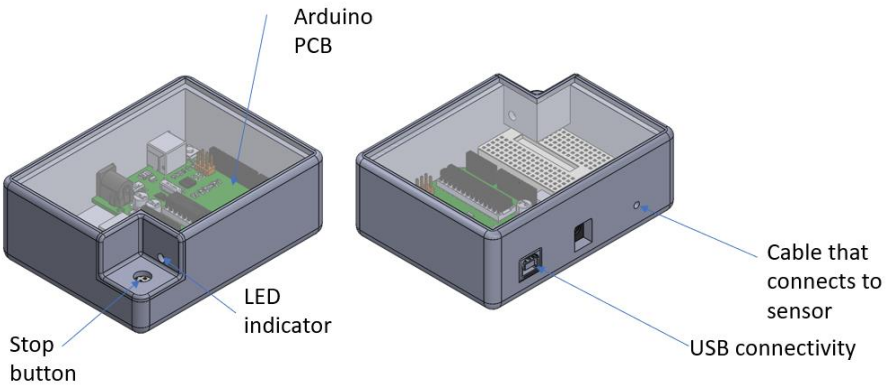


Figure 11a: The DAQ Box/Arduino Housing

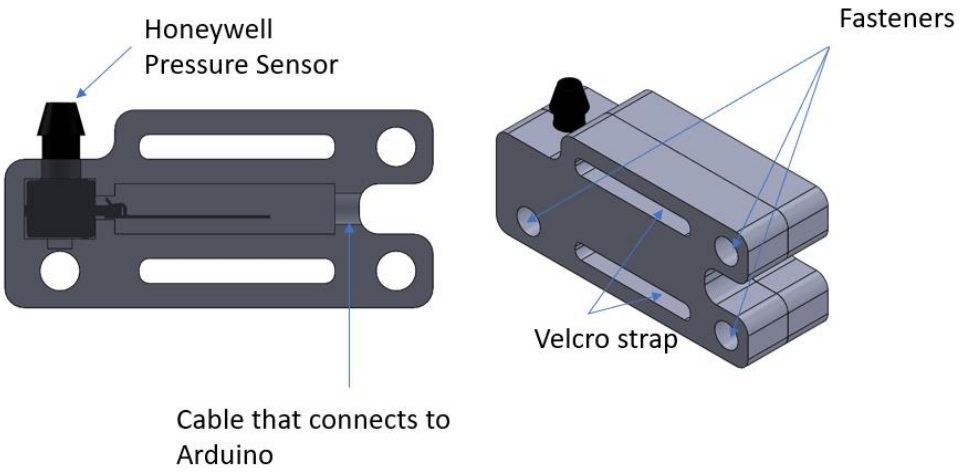


Figure 11b: Sensor Housing

5.2 User Interface

The data collection and analysis are performed via a program written in MATLAB (Appendix C - MATLAB Code). When run, the program begins calibration by finding the average pressure reading in the balloon before the train of four impulse is initiated. The calibration is performed for exactly 2 seconds. After that, the program turns on the red LED

indicator light on the DAQ Box which tells the user that the device is calibrated and ready for data recording. Simultaneously, a graph showing the live pressure reading within the balloon is displayed on screen as seen in Figure 14a. The user can now apply the train of four stimuli from an independent nerve stimulator. When the train of four test is complete, the user presses the stop button on the DAQ Box. This switches off the red LED indicator light on the DAQ Box, notifying the user that data collection has stopped. The program then tells the user the number of peaks identified, the calculated fade ratio, and asks the user if they would like to export the raw data and the data analysis (figure 14b). If the user indicated that they would like to export the data, they must input a name for the file. Finally, the raw data and the data analysis are exported to an excel file and a text file respectively.

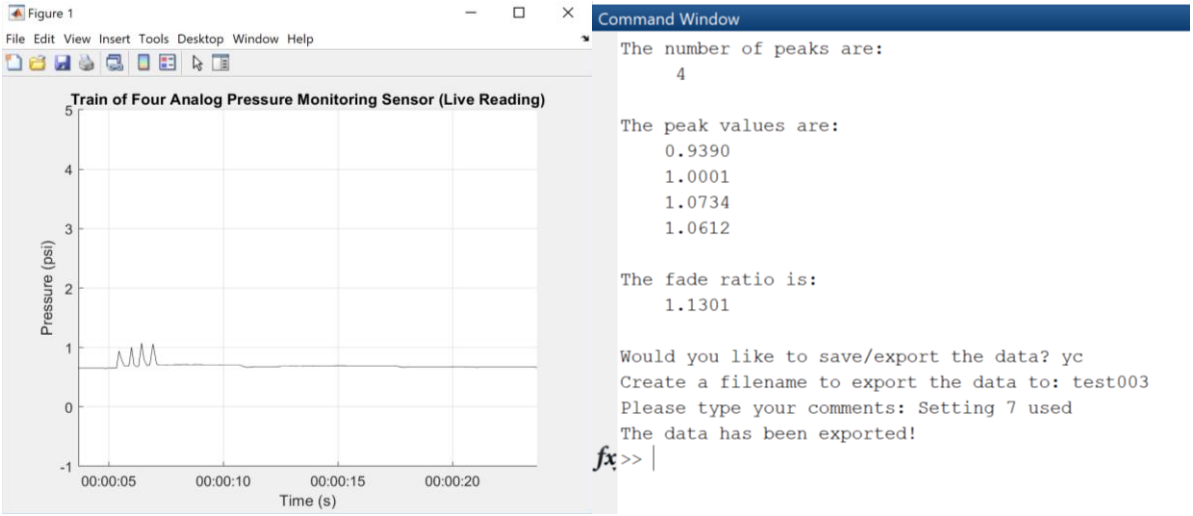


Figure 12a (left): User Interface - The Live Pressure Graph
Figure 12b(right): User Interface - The Command Window

5.3 Initial Prototype

The initial prototype used a syphon pump as a pressure balloon and was connected to a pressure transducer through a ⅜ in PVC tubing. The pressure balloon was sealed at one end in

order to maintain a closed system, and air was used as the working fluid. Athletic tape was used to fix the pressure balloon to the palm such that the thumb would rest on the cylindrical section of the apparatus. The change in pressure created by the response of the thumb was measured using a LabView program designed and calibrated for the pressure transducer.

While the early prototype was successful in capturing a response by the thumb, there were some areas of improvements identified for future iterations. Stiffness and geometry of the balloon were both factors affecting the response recorded by the transducer, with greater stiffness resulting in smaller pressures transferred to the working fluid and forces applied to the spherical portion of the balloon also resulting in smaller responses recorded. The volume of the pressure balloon also affected the sensitivity of the device, with larger volumes potentially resulting in lower pressures produced and decreased sensitivities. Observations of the device when in use indicated that oftentimes a portion of the response would be lost to a movement of the device instead of a deformation of the pressure balloon, requiring either better mounting or alternative positioning of the thumb.

5.4 Prototype Optimization

Through position testing using the nerve stimulator and the balloon attached to a pressure gauge, we were able to find the position that allowed for the greatest pressure differential created by the force of the thumb twitch. This occured when the hand was in a fist and the thumb was hitting the side of the index fingers' knuckles. We decided on two prototypes to be compared with extensive analysis.

The first (shown in Figure 15) is a full glove which is both easy and quick to put on a patient, and achieves a platform for the thumb to strike by sewing the fingers of the glove together. In order to stabilize the hand in this slightly unnatural resting position, we attached

velcro to the palm and tips of the fingers so the hand can curl into a fist independent of hand size. Laser cut acrylic plates are attached to the the thumb and the top of the hand where the thumb would land and held together with elastic strap so that the balloon would not have any side to side translation. The attachment to the hand is also using velcro as well in order to create the best hand position based on the twitch of the patient and the hand size. The balloon is held inside a fabric sleeve for protection and stabilization. Since the balloon is fully compliant, it is not necessary to replace it after use.

Figure 13: Black Glove Prototype with Analog Pressure Gauge

The second prototype (shown in Figure 16) is a mitten design that is versatile to accommodate many hand sizes and is easy to put on a patient. Much of this prototype is similar to the first; modifications were made to the positioning of the velcro as well as the inclusion of adjustment straps to fit as many hand sizes as possible. The acrylic plates were also made into a completely removable subunit attached via a button, therefore allowing the rotation of the mount for the balloon, which helps optimize the positioning for each individual patient.

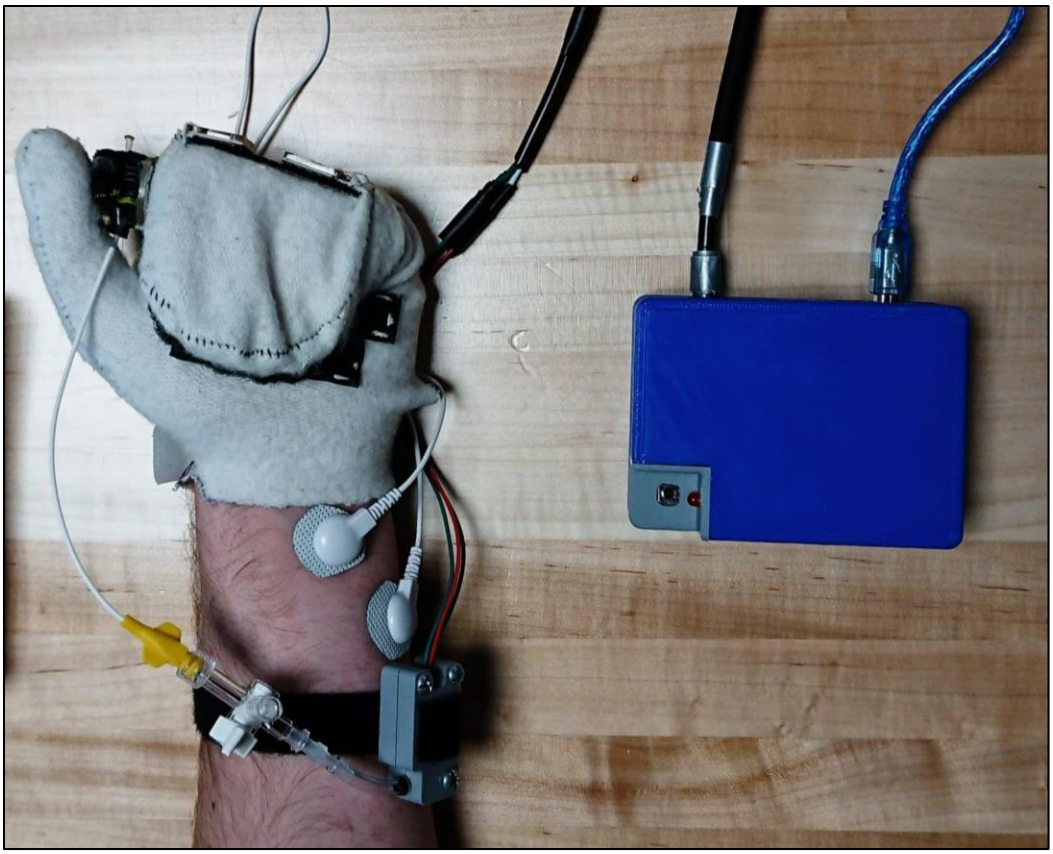


Figure 14: White Glove Prototype with DAQ Box

Due to limited selection of available balloons, the balloon could not be fully optimized, however our analysis told us that the balloon which would produce the most pressure was the smallest balloon available. The main conclusion of our optimization process was that the reduction in volume of tubing resulted in an increase in change in pressure. For that reason, we shortened the tubing connecting the balloon assembly to the pressure transducer. This was done by mounting the sensor directly to the patient's wrist using a custom made housing designed to attach to the forearm using a velcro strap, as seen in Figure 17. The housing for the sensor was 3D printed using PLA and was designed to accommodate wires connected to the pins by narrowing the exit port such that they could not be easily pulled out. This change brought our pressure change from ~0.2 psi to ~2.5 psi.

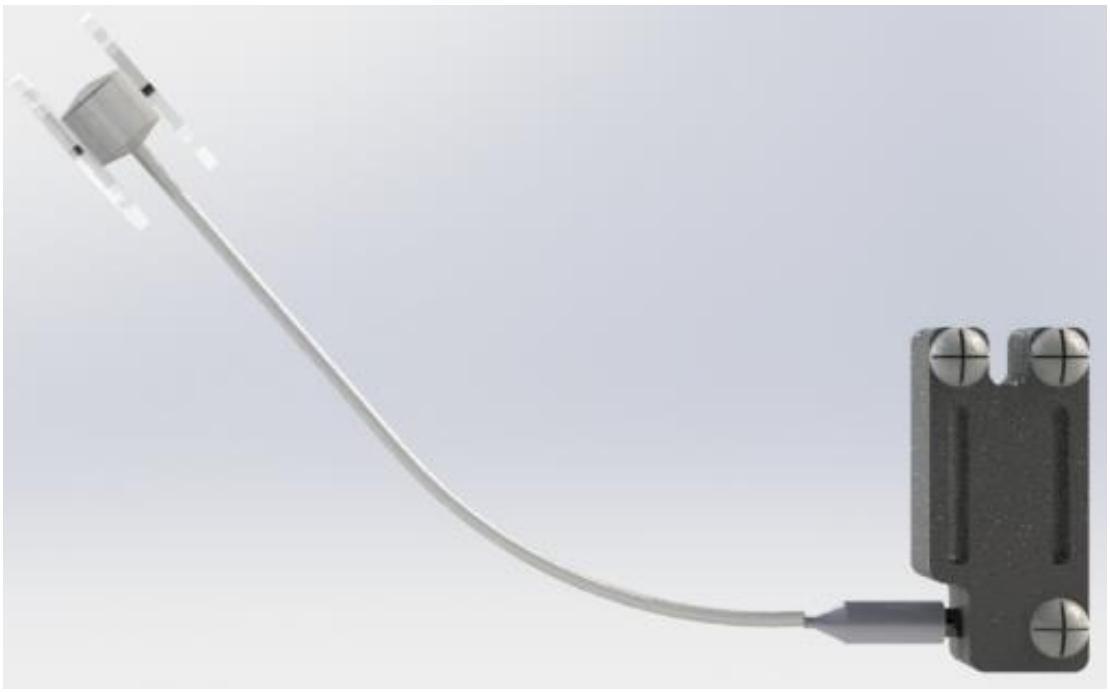


Figure 15: Sensor Housing System

Table 8 below summarizes the functional differences between both prototypes post testing, the following section (4.3) explains the testing in detail. The black glove produced a fade ratio average of about 101.78%, which is 4.45% closer to the expected 100% than the white glove. The standard deviation of the black glove is about 4.00% while the white glove is about 14.61%. Although the black glove produced data that was slightly closer and much more consistent than the white glove, it failed to capture the twitches of many of our subjects. The inconsistency of successful data collection with the black glove was unacceptable, so going forward the white glove will be the baseline for prototype modification.

Table 8: Comparing Fade Ratio Mean, SD, and Trial Consistency of Prototypes 1 & 2

	Black Glove (Prototype 1)	White Glove (Prototype 2)
Fade Ratio Mean:	1.0178	1.0623
Standard Deviation:	0.0396	0.1461
# of Successful Data Collection Trials:	7/34	28/34

In response to feedback and qualitative observations, there are several modifications recommended for the device. One such modification would be to the positioning or shape of the balloons, as one of the main causes for a failed test would be the response of the thumb moving in a direction not easily captured by the balloon. Other feedback indicated the need to remove more material from the back of the glove, such as cutting a hole out for a pulse sensor to be attached to one of the fingers. This modification is demonstrated below in Figure 15. Other potential improvements could be made to increase the sampling rate of the data acquisition system, whether it be through code optimization or more sophisticated hardware.

Figure 16: Modified White Glove Prototype for Pulse Monitoring

5.5 Prototype Testing

Testing of the prototypes was performed on fully awake volunteers. The objectives of these trials was to produce a consistent fade ratio of 1 when the train of four was applied, similarly to the theoretical fade ratio predicted for train of four testing. A total of 34 participants were tested, with each participant being tested three times on each glove. While only some participants were tested using the black glove due to time constraints, all participants were tested using the white glove. Prior to testing, all participants were given a description of the experiment and asked to sign a consent form. The values of these tests was not only to collect quantitative data but to also identify potential modes of failure for the device and circumstances in which it may not collect data properly.

5.5.1 *Methodology*

The study took approximately 15 minutes. The thumb length of 34 participants was measured with a ruler to draw the relationship between thumb length and pressure exerted. The electrodes of the nerve stimulator were placed on the forearm. These were standard ECG electrodes that are used on a regular basis in hospitals. The Peripheral Nerve Stimulator (PNS) provided a train-of-four electrical impulses to the nerve of the thumb through the electrodes placed on the skin of the arm. The PNS was calibrated to each participant by first selecting a zero amplitude and then, slowly increasing in increments of 10mA until 4 twitches in the thumb was observed. The current was not greater than 80mA, so that the process was safe for the participants.

After putting the prototype on, participants were asked to depress the balloon manually to ensure that it was set up correctly. The PNS then provided 3 sets of 4 impulses; the duration of each set was 10 seconds for a total of 30 seconds. The data was saved. The device and electrodes were detached and participants were asked to answer some follow-up questions, shown in Appendix D. No personal identifying information was recorded.

5.5.2 *Experimental Data Collection*

Once the device prototype has been completed, it will need to be tested on several volunteers in order to gauge its physical functionality as well as our data collection and analysis program. The goal of this is to collect data on the following: ease of use, effectiveness, accuracy, reliability of output results (correct number of peaks as well as proper fade calculations displayed), comfort, and overall efficacy of the device. The protocol for these tests can be found in Appendix E.

Besides this protocol, an analysis program will be run on the collected data for the purpose of identifying peaks in each TOF twitch set (count 0-4, display out of 4). Fade ratios between each twitch will also be calculated by this program and displayed. Thumb size will be measured to understand the correlation, if any, that exists between thumb size and fade ratio.

5.5.3 *Testing Results*

Figure 18 shows a typical TOF graph produced through our testing. Though the fade ratio looks nearly perfect, there is concern that having only ~4 data points per peak results in an inaccurate depiction of the data. This lack of granularity is due to the 12 Hz sampling rate and will be discussed in more detail in section 6.

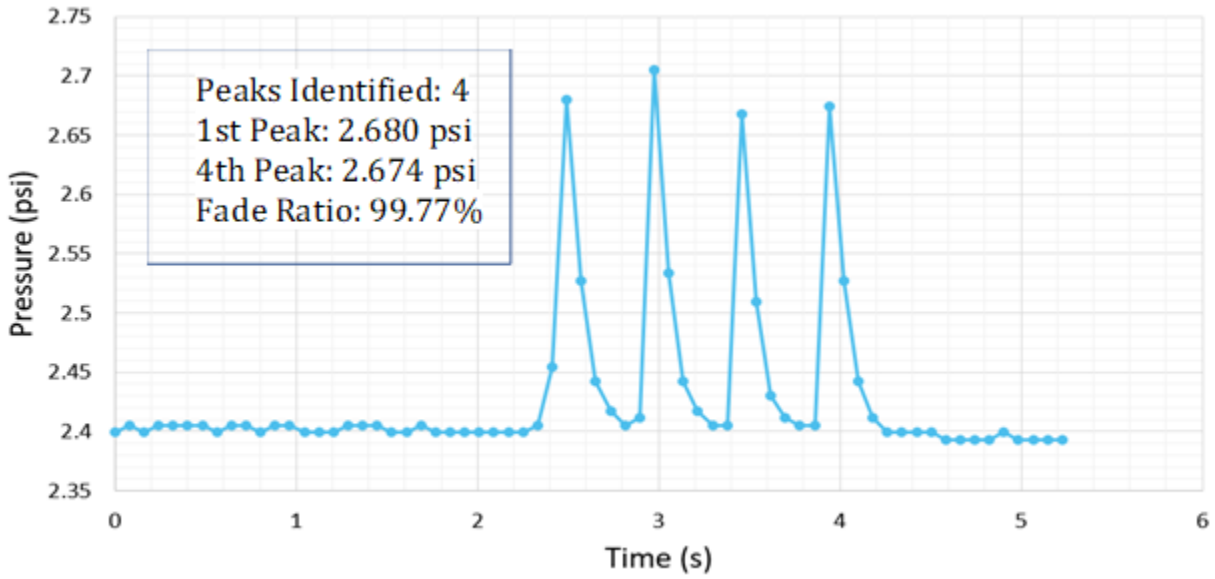


Figure 17: Raw Data from TOF Test with Linear Interpolation

Figure 19 shows a histogram of all samples collected. Although the mean is close to the expected mean of 100%, the standard deviation is too high for the data to be useful. This may be

due to the sampling rate as mentioned previously, but could also be due to improper positioning or electrode placement.

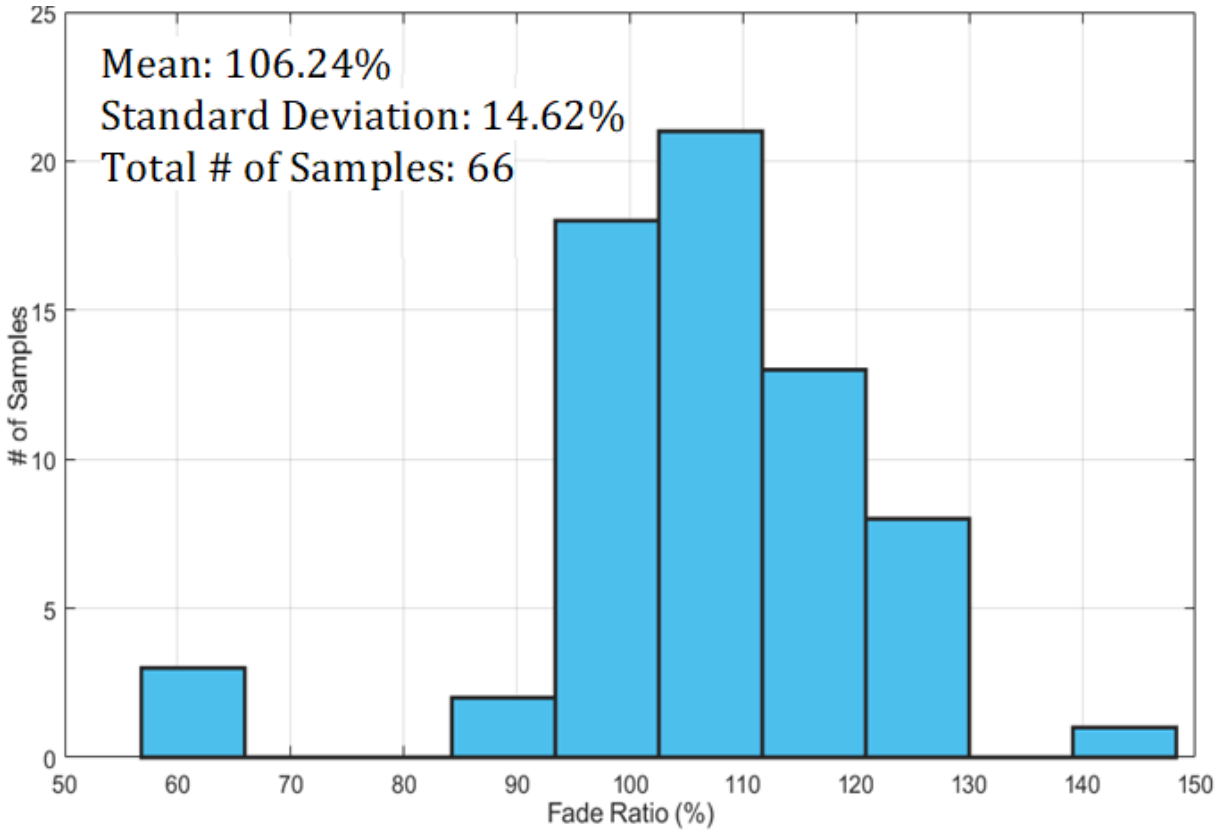


Figure 18: Histogram of All TOF Ratios

Figure 20 shows a scatter plot of fade ratio versus thumb length across all of our samples. The results suggest that there is no correlation between the length of a patient's thumb and the performance of the device.

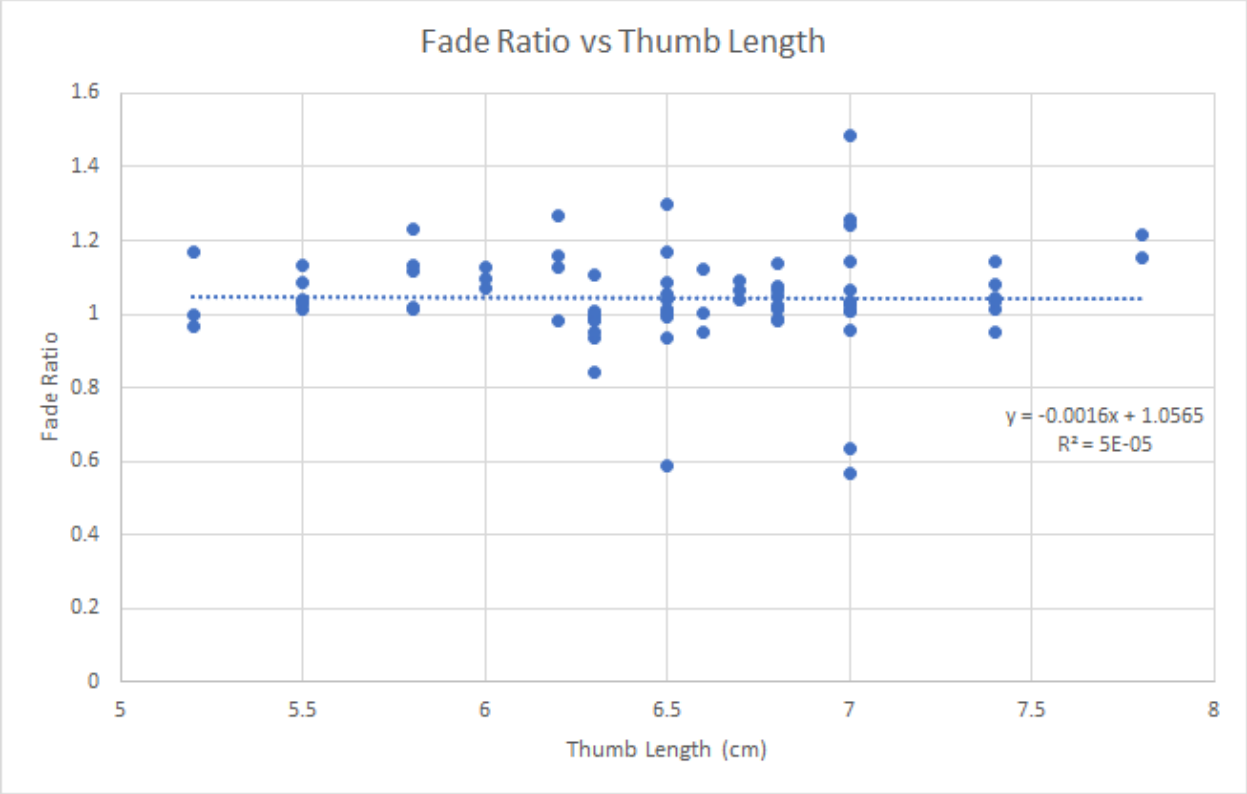


Figure 19: Scatterplot of Fade Ratio vs Thumb Length

5.5.4 *Patenting*

On April 19, 2019, a provisional patent was filed for the Train of Four Monitoring Device. Through Worcester Polytechnic Institute, an invention disclosure was created with signatures from all inventors. This was sent to the Office of Technology Commercialization at WPI and was used to create a provisional patent to protect the product idea. The provisional patent protects our idea for a 18 to 24 month period until working patent is filed. During this time the WPI Office of Technology Commercialization will decide if they will move forward in commercializing the patent. Ownership is split evenly between all inventors and with WPI.

6. Alternative Solutions

6.1 Bending Strain Sensors

Initial designs for the device included the use of specialized strain gauges to measure the amplitude of the response through the deflection of the gauge. Because conventional strain gauges are unable to support the amount of deformation produced by the thumb or other body parts, a specialized potentiometer capable of high deflection was used as a strain gauge instead. For this purpose, our team purchased FlexPoint Bend Sensors of varying lengths, which utilizes a carbon/polymer ink-based sensing material protected by a plastic coating. The amplitude of a given response would be measured through the voltage change resulting from the change in resistance of the sensor when deformed. Because the voltage output was typically in the millivolts, a wheatstone bridge was used to isolate the signal, which could then be amplified. Designs for this type of sensor focused on the thumb and typically involved a partial or fully gloved mounting system to be worn on the patient's hand. The sensor would be placed in a pocket in the glove and could be removed for cleaning after the surgery.

One of the advantages of this type of sensor was the reliability of the output. The unstrained resistance of the potentiometer was a stable value that would be returned to quickly with minimal hysteresis except in the case of very large deflections. The sensor was also very thin and non-obstructive to mount. However, one of the disadvantages of this type of sensor is the lack of disposability due to its higher cost. This requires the sensor to be cleanable and also takes time for the sensor to be remounted, as the glove and sensor could likely not be washed together. Another drawback to this type of measuring system was that the thumb must be able to demonstrate full range of motion to properly measure the response, which may not be possible in

scenarios where the hand is tucked under a blanket or otherwise restricted, which is common in many surgeries. For these reasons it was determined that using a pressure transducer would be a more viable option, as it allows for disposable sensing elements and usage in more restrictive surgical environments.

6.2 Conductive Ink Sensors

Due to an increasing need for flexible, low profile circuitry, conductive inks have seen increasing popularity in wearable sensors. These materials consist of inks with conductive nanoparticles such as silver, gold, copper, or carbon, and function by allowing an electrical current to pass through the path drawn by the ink (Sun et al, 2018). This allows for custom-shaped circuits to be drawn using the inks and greater flexibility when designing a sensing element. Similarly to conventional strain gauges, deformation to the circuit, such as tension or compression, will change the resistance of the circuit by changing the distance between the nanoparticles. This creates a change in voltage across the system, which could then be measured to determine the amplitude of the impulse.

Early prototypes were created using Bare Conductive Electric Paint, which was applied to computer paper. Sensors were generally rectangular in shape and contained a zig-zagging pattern of straight rectangular lanes traveling the length of the sensor called “passes”. While early prototypes were produced through careful measurement and hand painting, later iterations were produced through the use of laser cut stencils of specified dimensions. All prototypes tested were produced using hand painting techniques, however if this method were to be pursued then methods such as screen printing or inkjet printing would be used instead.

Despite advantages in versatility and rapid production of the prototypes, some of the drawbacks of the conductive ink prototypes included difficulty controlling the resistance of the

sensor as well as repeatability in producing sensors. Similar to the bend sensors, another limitation of the conductive ink sensors was the requirement for the body part measured to exhibit a full range of motion, which may not be possible in scenarios where in may be covered by a blanket or otherwise restrained.

6.3 Touch Force Sensor

Other designs similar to the hydraulic sensor include the use of force sensors designed for touch applications. These sensors would be mounted to a cylindrical apparatus that would be attached to a glove and held in place by the hand. The tip of the thumb would be placed on the sensor and apply a force would be applied by the thumb to the sensor in response to the stimulus. Advantages to this method include freedom of the back of the hand, preventing interference with IV lines and the ability to record data while the thumb has a limited range of motion. However, some drawbacks to this method include having to protect the sensor from contact with the skin to keep it sterilized and the need to wash parts or all of the system due to it not being completely disposable.

7. Conclusion and Recommendations

Our team was able to successfully design a working prototype which could recognize the twitches resulting from a train of four test, and output the magnitude of each individual twitch with respect to each other. The device was also able to recognize the number of twitches present and fade ratio, and save the data in a format that would be easily accessible for physicians without the need to buy expensive software. Our prototype was also able to produce and average fade ratio close to 1 for the population tested, which was the expected theoretical result for a train of four test on an anesthetized patient. However, there are some limitations and areas of

improvement for the device. The standard deviation of the results was 14.62%, a relatively high value for an application such as this. One possible reason could be that the relatively low sampling rate of 12 Hz (medical devices typically operate around 200 Hz) could have obscured the data. This low sampling rate could have been potentially caused by the arduino used, which was not suitable to displaying graphical data in real time. The solution to this problem would likely be to use a more powerful arduino or Raspberry Pi to perform the data collection. Another difficulty encountered with the project was correctly capturing the motion of the thumb. For some participants the thumb would move sideways and not directly downwards into the balloon, reducing the pressure change detected. Changes would likely have to be made to the mounting system or geometry of the balloon in order to better capture the data produced. However, if these problems can be resolved, the device should be fully operational and ready for use in the medical field.

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Appendix A- Interview Questions for Anesthesiologists

Introduce ourselves, our project, and the reason for this interview

- Currently, we are designing a device that can be used to monitor the level of anesthetization in patients. We have reached out to you to develop a better understanding of the potential needs and usage for a device of this kind.
- We can begin with the questions whenever you are ready

Questions:

- What is your position?
- How long have you worked in this position?
- Do you work closely with patients under anesthesia? (If yes, continue with questions)
- What kinds of anesthesia do you work with? (general etc.)
- Can you walk us through what it is like to set up and administer this type of anesthesia and the methods you use to monitor the level of anesthesia in patients?
- What devices do you currently use to perform these tests?
- What aspects of this process do you like?
- What aspects of this process do you dislike or wish you could change? (focuses on the process)
- Are there any common difficulties that you run into when performing these tests? What parts of these tests tend to be the trickiest to perform? (focuses on the method/device)
- Are there any factors which may make you feel less certainty in the results of a test?
- Do you believe that the way you perform these measurements is likely to change in the future? If so, what changes do you expect to occur?
- If a new device were to be made to assist in taking measurements for a train of four test, what would be the key features for it to possess?
- Do you have a preferred method in which this device would collect data, and are there any specific user-friendly qualities you would like to see in the interface of this device?
- What would you imagine this device would look like?
- One of the potential feature of this device would be the ability interface with existing medical equipment. Do know any common brands/devices in an operating room which can be interfaced with by various devices?
- Is there anything else you would like to add?

  Thank you for your time. If you have any other thoughts or questions, please contact us through email or phone.

Appendix B - Survey

Thank you for taking the time to complete this survey. This should take no more than 10 minutes.

Our group is designing a unique device that assists medical professionals in monitoring a patient's level of neuromuscular blockade during surgery. Neuromuscular blockade refers to the anesthetization of a patient to temporarily paralyze them. The standard way of quantitatively measuring neuromuscular blockade is called Train-of-Four (TOF). TOF involves the use of a peripheral nerve stimulator (PNS) which provides a train of four electrical impulses to the patient's nerve through electrodes placed on the skin.

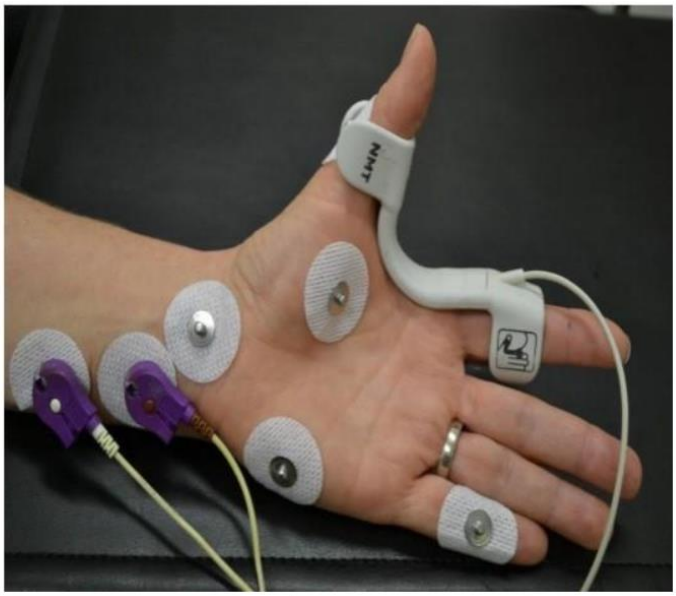
Our group is currently considering different designs for a TOF device. We would like your input on the designs we are considering. For this survey, you will be shown images of four different designs. These designs all enable the physician to attach a sensor to a patient who is going under anesthesia. For each design, you will also be presented with some practical information about the design. After each design, you will answer some questions about it.

→

Please look at the following image carefully.

The "thumb and index finger straps" design shown below, is reusable and easy to place correctly.

However, it is not adaptable, it is more expensive than the other designs, and it is not possible to use it on the tibial nerve (leg) in addition to the ulnar nerve (arm).



How easy do you think it would be to use this design?

- Very easy
- Easy
- Slightly easy
- Not that easy
- Not easy at all

Do you think it would be possible to put this design on most patients?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Do you have any thoughts/concerns about the "thumb and index finger straps" design?

→

Please look at the following image carefully.

The "thumb and wrist sleeve" design shown below, is reusable, adaptive, stable, fairly inexpensive and easy to place correctly.

However, it is not possible to use it on the tibial nerve (leg) in addition to the ulnar nerve (arm). Moreover, it might be restrictive to movement.

How easy do you think it would be to use this design?

- Very easy
- Easy
- Slightly easy
- Not that easy
- Not easy at all

Do you think it would be possible to put this design on most patients?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Do you have any thoughts/concerns about "thumb and wrist sleeve" design?

←

→

Please look at the following image carefully.

The "band-aid" design shown below, consists of tape wrapped around the thumb and palm. It is the only design that can be used on the tibial nerve (leg) in addition to the ulnar nerve (arm) by varying the pad shape. It is inexpensive and easy to produce.

However, it allows for more mistakes when putting it on.

How easy do you think it would be to use this design?

- Very easy
- Easy
- Slightly easy
- Not that easy
- Not easy at all

Do you think it would be possible to put this design on most patients?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Do you have any thoughts/concerns about the "band-aid"?

←

→

Please look at the following image carefully.

The "thumb sleeve" design shown below, is reusable, adaptive, easy to place correctly, non-restrictive and fairly inexpensive.

However, it might slide off the thumb out of place and it is not possible to use it on the tibial nerve (leg) in addition to the ulnar nerve (arm).

How easy do you think it would be to use this design?

- Very easy
- Easy
- Slightly easy
- Not that easy
- Not easy at all

Do you think it would be possible to put this design on most patients?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Do you have any thoughts/concerns about "thumb sleeve" design?

←

→

To recap, here are all the designs that you viewed.

Thumb & Wrist Sleeve | Thumb Sleeve | Thumb & Index Finger | Band-aid

Please rank the designs you saw in order of preference.

"Thumb and wrist sleeve"

"Thumb sleeve"

"Thumb and index fingers strap"

"Band-aid"

Do you have any other comments that you would like to add about any of these designs or your ranking?

←

→

Please indicate your gender.

Male

Female

Other

Prefer Not to Say

Please indicate your ethnic background.

African American/Black

Asian/Pacific Islander/South Asian

Caucasian/White

LatinX

Middle Eastern

Native American/Alaskan Native

Multi-Racial

Other

Prefer Not to Say

Please indicate your age in years.

How much knowledge do you have about the medical field?

Very Little				Very Much

How much experience do you have about in the medical field?

Very Little				Very Much

How much knowledge do you have about the anesthetic devices?

Very Little				Very Much

Do you work in the medical industry?

No

Yes

←

→

How are you participating?

MTURK

WPI

←

→

MTURK Participants--Here is the code:

MEDDEVICEMQP

This is the end of the survey.

Thank you for participating in the survey. We appreciate the time you took to look through the designs and rank them. The information you provided is going to be very helpful as we finalize our design.

If you have any questions about the project feel free to email the group at gr-TOF@wpi.edu

←

→

Appendix C - MATLAB Code

TOF_HSC005_v82.m

```
%% TOF Script: Honeywell HSC Analogue Pressure Sensor Script v8.2
% Version Information: This script reads input voltage data from an
% analogue presssure sensor. The script then converts the voltage signal
% to a pressure reading and displays the pressure reading live on screen.
% The script stores the pressure reading vs time and asks user to export
% the data to an excel file. The script then calculates train of four
% ratio and exports the peaks values and fade ratio to a text file.

%% For use with Honeywell HSC Analog Pressure Sensor: HSCSAND005PGAA5
% Orient the sensor flat on its back with the pins facing downwards and
% the barbed port pointing away from the table. There are four pins. The
% pins are pin 1 (no connection), pin 2 (Vsupply),pin 3 (Vout) and pin 4
%(ground).  Vsupply gets connected to the 5V power supply on the arduino,
% Vout gets connected to 0A0 on the arduino and Ground to GND on the
% arduino.

%% Clear previous arduino/MATLAB data
clear; close all; clc;

%% Specify the port and board type
a=arduino('COM5', 'Uno');

%% Create a new animated graph and format axis
figure
ax=gca;
set(ax,'XGrid','on','YGrid','on','YLim',[-1 5]); %set limits of y-axis

T0=datetime('now');
TOF_live=animatedline;
%% Calibration
i_c=1;
tic
timer_calibration=2; %take 2 seconds worth of data in order to calibrate
while toc<timer_calibration
    v_cal=readVoltage(a,'A0');
    v_cal_store(i_c,1)=v_cal;
    i_c=i_c+1;
end
% calculate the average calibration value
cal_val=mean((v_cal_store-0.5)/0.8);
```

```
%% Create initial conditions for storing the data
P_store=0;
t_store=T0;
k1=1;
%% Configure Button & LED Indicator functionality
configurePin(a, 'D2', 'PullUp'); %set button status to 0 when depressed
button_status = 1; %set default button status to 1
%%
tic %start timer
while button_status==1 % run until button is pressed
writeDigitalPin(a, 'D4', 1); %turn RED LED on
button_status = readDigitalPin(a, 'D2'); %check button status
%% Read sensor voltage data
v_out=readVoltage(a,'A0');
P_applied=(v_out-0.5)/0.8; %equation that governs the sensor
%For equation: Honeywell TruStability Board Mount Pressure Sensors
% Datasheet (HSCSAND005PGAA5)
t=datetime('now')-T0;
%% Display Live updates to the graph
set(ax, 'XLim', datenum([t-seconds(20) t]));
datetick('x','keeplimits')
addpoints(TOF_live,datenum(t),P_applied); %adds points
drawnow %tells MATLAB to draw now
an=animatedline(datenum(t),P_applied); %plots the figure

%% Format graph properties
xlabel('Time (s)'); ylabel('Pressure (psi)');
title('Train of Four Analog Pressure Monitoring Sensor (Live Reading)');

%% Store the data in a character array and a double
t_store(k1,1)=datetime('now');
P_store(k1,1)=P_applied;
k1=k1+1;
end
timer=toc; %how long did we collect data for? i.e. how long did while loop
% run for
writeDigitalPin(a, 'D4', 0); %turn RED LED off
%% Format the data from t_store into a nicer format for table
t_store=datestr(t_store,'mm/dd/yy HH:MM:SS:FFF');
for idx=1:length(t_store)
t_store_split(idx,:)=strsplit(t_store(idx,:),' ');
```

```
82 -    end
83
84      %% Create a table and Name the Header rows (for saving -later on)
85 -    T=table(t_store_split(:,1),t_store_split(:,2),P_store);
86 -    T.Properties.VariableNames={'Date','Time_hh_mm_ss_msmsms', 'Pressure_psi'};
87
88      %% Data Analysis
89 -    time=linspace(0,timer,length(P_store));
90 -    plot(time,P_store,'-')
91      %--------------------------------------------------------------------------
92 -    delta=cal_val+0.1; %this is the threshold value, decrease it for increased
93      % sensitivity in analysis of the data/peaks
94      %--------------------------------------------------------------------------
95 -    peaks=findpeaks(P_store); %this function finds all the peaks in the data
96      % since the data is inherantly noisy we will filter out values below the
97      % threshold using this for loop. the for loop sets all values that
98      % are below the threhold value "delta" to zero
99 -    for i=1:length(peaks)
100 -        if peaks(i)<delta
101 -            peaks(i)=0;
102 -        else
103 -            peaks(i)=peaks(i);
104 -        end
105 -    end
106
107 -    peaks=nonzeros(peaks); % we remove all the values that are zero from peaks
108      % essentially we are removing all the values that we just made 0.
109
110 -    if length(peaks)>1
111 -    fade=(peaks(end))/peaks(1); % this equation calculates the fade ratio
112
113     % displays the data analysis in the command window
114 -    disp("The number of peaks are:")
115 -    disp(length(peaks))
116 -    disp("The peak values are:")
117 -    disp(peaks)
118 -    disp("The fade ratio is:")
119 -    disp(fade)
120 -    else
```

```
121 -    disp('Could not identify peaks. Raw data is still available for export');
122 -    end
123      %% Export the raw data & analysis data to a file
124
125      % ask the user if they would like to save data. they are given three
126      % options y - yes, n - no & yc - yes with comments. The comments will
127      % be exported as part of the data analysis text file
128 -    checker=1;
129 -    while checker==1
130 -    save_yn=input('Would you like to save/export the data? ','s');
131 -    switch save_yn
132 -    case 'yc'
133      % Export the table data to a user specified MS Excel filename
134 -    fname=input('Create a filename to export the data to: ','s');
135 -    filename=strcat(fname,'_raw_data.xls');
136 -    writetable(T,filename);
137
138      % Export the analysis data to a text file
139 -    filename_analysis=strcat(fname,'_data_analysis.txt');
140 -    fid=fopen(filename_analysis,'wt');
141 -    if length(peaks)>1 % if code found peaks, it will write value to text file
142 -    fprintf(fid,'%s\n', 'Number of peaks: ');
143 -    fprintf(fid,'%f\n', length(peaks));
144 -    fprintf(fid,'%s\n', 'Train of four peak values (psi): ');
145 -    for i=1:length(peaks)
146 -    fprintf(fid,'%f\n', peaks(i));
147 -    end
148 -    fprintf(fid,'%s\n', 'The fade ratio is: ');
149 -    fprintf(fid,'%f\n', fade);
150 -    else %if code cannot identify peaks, raw data will still export
151 -    fprintf(fid,'%s\n', 'The code was not able to identify any peaks!');
152 -    end
153 -    fprintf(fid,'%s\n', 'Comments: ');
154 -    comments=input('Please type your comments:','s');
155 -    fprintf(fid,'%s\n', comments);
156 -    fclose(fid);
157 -    disp('The data has been exported!')
158 -    checker=0;
159 -    case 'y'
```

```
fname=input('Create a filename to export the data to: ','s');
filename=strcat(fname,'_raw_data.xls');
writetable(T,filename);
filename_analysis=strcat(fname,'_data_analysis.txt');
fid=fopen(filename_analysis,'wt');
if length(peaks)>1 %if code found peaks, it will write value to text file
fprintf(fid,'%s\n', 'Number of peaks: ');
fprintf(fid,'%f\n', length(peaks));
fprintf(fid,'%s\n', 'Train of four peak values (psi): ');
for i=1:length(peaks)
fprintf(fid,'%f\n', peaks(i));
end
fprintf(fid,'%s\n', 'The fade ratio is: ');
fprintf(fid,'%f\n', fade);
fclose(fid);
disp('The data has been exported!')
else %if code cannot identify peaks, raw data will still export
fprintf(fid,'%s\n', 'The code was not able to identify any peaks!');
end
checker=0;
case 'n'
disp('The data has NOT been saved!')
checker=0;
otherwise
disp('Please enter either "y" (yes), "n" (no) or "yc" (yes with comments)')
end
end
```

Appendix D - Testing Questionnaire

Please answer the following questions for the black glove.

How comfortable was the glove?

1	2	3	4	5
Not At All				Very

How restrictive did it feel?

1	2	3	4	5
Not At All				Very

How loose did it feel?

1	2	3	4	5
Not At All				Very

How did you feel about the involuntary sensations?

1	2	3	4	5
Not Comfortable At All				Very Comfortable

How likely would you be to recommend this prototype to a hospital?

1	2	3	4	5
Not At All				Very Likely

How easy was it to put on?

1	2	3	4	5
Not At All				Very

How easy was it to take off?

1	2	3	4	5
Not At All				Very

Do you have any design feedback?

Other comments:

Please answer the following questions for the white glove.

How comfortable was the glove?

1	2	3	4	5

Not At All Very

How restrictive did it feel?

1	2	3	4	5
Not At All				Very

How loose did it feel?

1	2	3	4	5
Not At All				Very

How did you feel about the involuntary sensations?

1	2	3	4	5
Not Comfortable At All				Very Comfortable

How likely would you be to recommend this prototype to a hospital?

1	2	3	4	5
Not At All				Very Likely

How easy was it to put on?

1	2	3	4	5
Not At All				Very

How easy was it to take off?

1	2	3	4	5
Not At All				Very

Do you have any design feedback?

Other comments:

<u>Demographics</u>

Please indicate your gender.
Male
Female
Other
Prefer not to say

Please indicate your height.

Please indicate your weight.

Please indicate your age in years.

Please indicate your ethnic background.

African American/Black
Asian/Pacific Islander/South Asian
Caucasian/White
LatinX
Middle Eastern
Native American/Alaskan Native
Multi-Racial
Other/Prefer Not to Say

Appendix E - Testing Protocol

Goal: Per subject, record sets of three separate TOF twitch groups (4 peaks per group) with both the prototype 1 (black glove) and prototype 2 (white glove)

General Procedure: All recordings are at 12 Hz

1. Have subject read and fill out informed consent form, go over the entire protocol verbally and make any clarifications necessary. Continue if the subject agrees to do so.
2. Prepare electrode sites (area over abductor pollicis brevis muscle on hand for EMG and the forearm for nerve stimulation). This includes disinfecting with alcohol and shaving away hair if necessary.
3. Apply nerve stimulator electrodes to subject's forearm, calibrate
4. Mount prototype 1 (black glove) TOF device
5. Begin a test recording and have subject depress twitch device manually to ensure there are no issues with the setup. Do not save this data. Continue if everything is functioning.
6. Record 3 individual TOF twitch sets (3 sets of 4 twitches)
7. Detach device and electrodes.
8. Remove prototype 1 device and stimulator, prepare electrode site as necessary
9. Reattach nerve stimulator electrodes and calibrate, preparing site as necessary
10. Mount prototype 2 (white glove) TOF device
11. Begin a test recording and have subject depress twitch device manually to ensure there are no issues with the setup. Do not save this data. Continue if everything is functioning.
12. Record 3 individual TOF twitch sets (3 sets of 4 twitches)
13. Remove all equipment from subject
14. Debrief subject and have them fill out post-procedure survey