Integrating E-Textiles, Nanotechnology, and AI to Enhance Physiological Data Acquisition

Project Number: SR-EAST2-134-T

Abstract

Technology integration is becoming increasingly common across many fields in science and engineering as a means of developing novel ways of addressing complex challenges. Utilizing and integrating advances in materials sciences, nanotechnology, artificial intelligence, electrical engineering, and computer networking this project designs and constructs a wearable mid-fidelity prototype that accurately and reliably measures and analyzes critical human physiological functions. Moreover, while the prototype incorporates cutting-edge technologies, it does so in a way that is low-cost, sustainable, durable, and accessible for users with diverse needs and abilities. Finally, the device has the capacity to store and stream longitudinal and real-time biofunction data using secure IoT technology.

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Modern advancements in science and engineering have enabled the rapid increase in virtual environments throughout many economic and social sectors. The onset of the COVID-19 pandemic in 2020 accelerated these technological developments especially in the healthcare industry, leading to the widespread and global use of telemedicine (Doximity, 2024). Telemedicine, also referred to as e-health, is a healthcare delivery system in which doctors and patients interact in a virtual clinical setting. In the first quarter of 2020, the number of telemedicine consultations in the US rose by 766% (Shaver, 2022) and between 2019-2023 the use of virtual healthcare worldwide nearly doubled and this growth trend is projected to continue (Lee, 2024; Statista, 2024; Zauderer, 2024).

This expansion has enhanced access to healthcare for many people in the US and across the world. This is especially the case for those with barriers to traditional medical care (Karimi**,** 2024; Hswan, 2021)**.** However, there are notable drawbacks to telemedicine as well. Because it is contactless, healthcare providers are unable to directly collect critical health information, namely vital signs such as heart rate and respiration (Khoong, 2024). In its current state, telemedicine lacks the technology to carry out this basic task.

The goal of this project is to bridge this telemedicine data gap by integrating diverse fields of science and engineering to develop a novel solution. Such technology integrations are becoming increasingly common as a means of generating new ways of addressing complex challenges (Foster, 2023). The challenge that this project seeks to address is how advances in materials science, nanotechnology, electrical engineering, artificial intelligence, and the Internet of Things computer networking can be used to develop a novel and broadly accessible sensor system that measures key physiological functions with comparable accuracy to commercial equipment. To assess the feasibility of this idea, the project team developed a mid-fidelity prototype that collects, measures, stores, and transmits key biofunctions in real-time.

Phase 1: Background

During this initial phase, the project team researched wearable sensors that measure vital signs. While biosensing systems are currently available on the market, they do not directly or sufficiently address or resolve the data acquisition gap created by virtual healthcare. Many of these systems take the form of either personal wearable devices, such as smartwatches, or medical-grade wearable instruments, typically by prescription (Kang, 2022). A wearable device is an independent and noninvasive apparatus worn directly on the human body or on clothing that can measure basic physiological functions, such as respiration rate, heart rate, and oxygen saturation of the blood (Hemapriya, 2017). However, many studies show that the data derived from personal wearable devices are insufficiently accurate for medical use (Ford, 2022; Bent, 2020; and Hahnen, 2020) and, in some cases, can jeopardize health outcomes because of these inaccuracies (Hartley, 2024 and Sjoding, 2020). This is, in part, due to the inaccuracy of patient-reported vital signs (Metlay, 2024). Moreover, these devices are often costly and not covered by medical insurance (Luong, 2025; Wetman, 2022; and Hswan, 2021). In addition, these devices do not measure all key biofunctions, such as forced vital capacity.

Prescription-based wearable instruments used by individuals provide more accurate measures of biofunctions but have notable limitations. First, many medical-grade wearable devices are expensive, some require subscriptions for monitoring or connectivity, and not all are covered by insurance (Wetman, 2022 and Kolski, 2020). Second, some medical devices designed for measuring biofunctions utilize electrodes to connect the wearer to the measurement instrument. However, a long-recognized drawback of electrode-based devices used to measure biofunctions is skin injury, especially with prolonged or repeated use among the elderly and disabled (Holm, 2024 and Thyssen, 2010). Third, younger individuals or those with disabilities may interfere with the device and prevent it from working as intended. (Wei, 2019). A fourth problem is the inability of doctors to access data collected by the units since most do not transmit the biofunction data to healthcare providers in real-time (Mortimer, 2022).

Phase 2: Engineering Question, Goals, and Constraints

The background research identified existing measurement instruments for vital signs and focused attention on the continuing areas of need. This enabled the research team to clearly identify research needs and develop a cogent research question. Following this, the project goals were established.

Research Questions

1. Technology Gap: Can this telemedicine gap be bridged so that healthcare providers can have access to real-time patient vital signs during telemedicine visits?
2. Technology Integration: Can advances in emerging fields of science, engineering, and technology help innovate a novel approach to bridging the telemedicine gap?

These two questions focus on whether advancements in various fields of emerging science and engineering can be integrated to address complex issues that are of critical importance in ways that are low-cost and broadly accessible to the general population? The challenging issue this project undertakes is the acquisition of critical physiological function data in a virtual healthcare environment.

Project Engineering Goals

Six specific goals were developed to guide the engineering process.

1. Utilize advancements in materials science, sensor technology, biomedical engineering, and sustainable energy technology to acquire key physiological data that cannot be obtained during virtual Telemedicine consultations.
2. Integrate materials and processes to design and build a low-cost, noninvasive, compact, and durable mid-fidelity prototype with comparable accuracy to commercial-grade equipment. A mid-fidelity prototype is a working device that has a clear conceptual design and can visually demonstrate overall functionality and component interactions. It is appropriate for initial testing and when repeated iterations are anticipated (D-labs, 2025). As a mid-fidelity device, this prototype is not intended and should not be used for

any diagnostic or medical purposes.

3. Design and construct a system of biofunction sensors that adhere to Universal Design Principles (UD), with a focus on accessibility for users with diverse needs and abilities.
4. Incorporate Artificial Intelligence (AI) to enhance the system's customizations.
5. Develop a prototype that incorporates both traditional and sustainable energy sources.
6. Create a mobile application that accurately displays and securely transmits physiological functions using Wi-Fi and IoMT networking.

To achieve these engineering goals, the project designed, constructed, and tested a working prototype. The location of this work was done in both a home setting and at an anatomy laboratory at Mount St. Mary's University (MSMU). The student researchers worked under the guidance of two teachers, both PhDs, who served as the Direct Supervisors for the project. In addition, a Mount St. Mary's University Biology professor served as the project's Anatomy and Physiology expert and a Maryland-licensed Physician's Assistant, who is the Director of the Mount St. Mary's University Physician's Assistant Program, served as medical expert. The project underwent research reviews by Mount St. Mary's University's Institutional Review Board and the Capitol Area Science and Engineering Fair's Science Review Committee (Appendix A). The project's review application was approved by both bodies prior to prototype testing.

Project Constraints and Mitigations

This was a complex engineering project that involved multiple phases, a wide array of materials and equipment, and a diversity of activities. To help ensure project success, the team of student researchers identified possible constraints and hazards that might hinder the project or pose a risk to the project team members. Efforts were made to minimize and mitigate these issues.

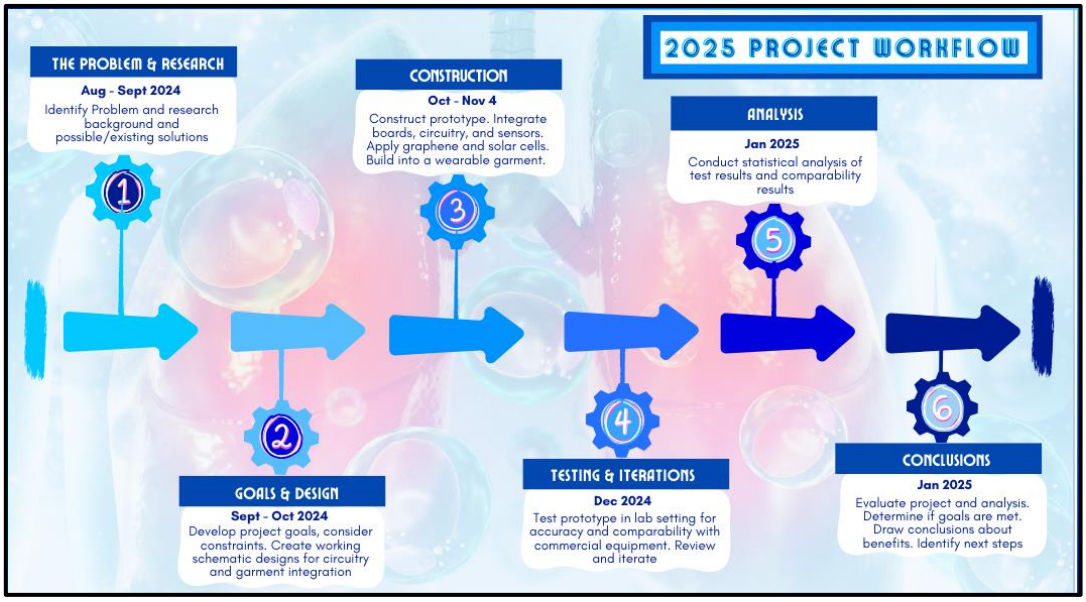
1. ***Budget Constraints***. There are several budget-related constraints. First, some of the equipment needed to test the prototype is high cost, such as the commercial spirometer and high-powered digital microscope. Student researchers addressed this constraint by

obtaining approval to use equipment from a local university research anatomy lab, including a spirometer and ECG machine. Second, while individual components for the prototype are not expensive, the construction and testing process can result in damaged materials, such as from soldering and power overloads. The budget constraint was addressed by using materials conservatively and with care to minimize waste and prevent damage to materials. Third, the project was able to minimize expenditures by using materials from previous projects. Student researchers also secured donated equipment and materials (chiefly from parents), including electronics and a 2000x digital microscope used for precision electronic component placement, precision soldering, and recording images of project materials. Finally, a project supervisor was able to obtain deeply discounted subscription pricing from *Blynk*, the internet hosting service provider used for the mobile application (Appendix B).

2. ***Time Constraints***. This project had a brief six-month time limit, a challenging timeframe for a complex, multiphase project. Several measures were taken to address this constraint. First, a project workflow timetable was created to help the project remain on pace (Figure 1). Second, efforts were also made to improve work time through a careful division of labor among the student researchers based on interest and skill specialization (Appendix C). Third, the researchers held regular collaboration meetings to assess the project's progress. Fourth, forward-planning took place to schedule meetings with the project's advising "qualified" scientist and the licensed medical professional, both of whom oversaw project testing. Moreover, anticipated work time that needed to be carried out at the Mount St. Mary's University Anatomy lab, which holds the commercial grade equipment used in the Prototype's testing, was scheduled in advance of project due dates.

Figure 1

Project Workflow Timetable



A work timeline was developed to ensure efficient pacing for the six-month project.

Image by Student Researchers.

3. ***Project Complexity.*** This project consisted of several goals and multiple components. These types of complex projects often face risks associated with prototype functionality and quality (Hewitt, n.d.), especially if pursued in a strictly linear way. Project advancement could easily be slowed if one part of the project, even a minor component, encountered a setback. Rather than pursuing a linear approach, student researchers opted to divide the project into specific phases and stages (subphases). Moreover, each student focused on specific areas of the project based on interests and skills. This was especially useful during the construction and testing/iteration phases. It allowed specific parts of the project to be designed, constructed, and tested/iterated and to move forward at an efficient pace, without being slowed by other parts of the project that moved at a different pace. It was essential, however, for both team members to closely collaborate to

ensure that decisions and changes made to one part of the project did not adversely impact other parts of the project. Team members also regularly reviewed the project goals to ensure that the work remained consistent with the goals.

4. ***Testing Constraints.*** There were several constraints that placed limits on how the prototype was tested. The first testing constraint was time related. The project was required to undergo two extensive reviews before testing could begin. The time it took for the reviews to be completed and the review requirements led researchers to the decision to modify the scope of testing. Rather than testing the prototype using a sample size of 15-20 participants, as originally planned, prototype testing used the two student researchers as test subjects. This had two negative impacts. First, it limited feedback on the UD features of the prototype and mobile application. Second, it limited the validity of the project's findings. Broader testing can be done at a later date to address these issues. A second testing-related constraint was the inability of researchers to test a broad selection of possible scenarios that might arise with the prototype's use (Keyploy, 2024). Since it is not possible to test for every possible use, the student researchers selected several common interactions.
5. ***Safety Risks.*** Because the project involved activities that carry some risks, such as soldering and physical activities during the testing phase, preventing harm and minimizing risks to those involved in the project was important. A key measure to reduce risks during all project phases was the requirement that an adult project supervisor be present at all times during construction, testing, and iterations. All tests were conducted under the supervision of a licensed medical professional, a qualified scientist, and the project's direct supervisor. Finally, a risk assessment and mitigation plan was developed and followed throughout the project (Appendix D).

Phase 3: Engineering Design

This project was developed using a generally accepted engineering design process that

is appropriate for mid-fidelity prototyping. It was also divided into specific phases and stages for efficiency in addressing project goals. Two schematics were developed to serve as blueprints for the prototype's construction and testing iterations. First a general schematic detailing sensor and other component placement was designed. Next, the wiring schematic was developed to clearly identify the circuitry connections.

Design Stage 3.1: Universal Design Principles

The Universal Design features were defined at this early stage to ensure their effective integration into the prototype. In engineering, Universal Design (UD) refers to designing products and processes that can be easily used by a wide diversity of people with minimal alterations (Burgstahler, 2009). There are seven core principles of UD.

- Equitable Use. The device and its functional components are designed and priced for a broad range of users.
- Flexibility in Use. The device and its functional components are engineered to accommodate a diversity of abilities and preferences.
- Simple and Intuitive. The instrument is designed and constructed so that it is easy to operate by users with various knowledge levels and backgrounds with no special or technical skills required.
- Perceptible Information. Necessary information for the device's operation is clearly communicated to users with varying abilities and backgrounds.
- Tolerance for Error. The instrument is designed to withstand unintended use.
- Low Physical Effort. A diverse range of users can operate the device with minimal effort.
- Size and Space for Approach and Use. The scale of the device and the placement of components are appropriate for users of diverse sizes, mobility levels, and postures.

Design Stage 3.2: Physiological Functions Selection

During this stage, the project focused on identifying which physiological functions should

be measured to meet the project goals. The project team decided to measure biofunctions commonly acquired during telemedicine consultations (Johns Hopkins Medicine, 2022).

- Heart Rate (HR) - the number of times the heart beats per minute.
- Respiration Rate (RR) - the number of breaths taken per minute.
- Forced Vital Capacity (FVC) - a measure of the maximum volume of air that can be forcefully exhaled after taking a deep breath.
- Blood Oxygen Saturation Percentage (SpO2) - the percentage of oxygen-saturated hemoglobin in a sample of blood relative to the total hemoglobin levels in a sample of blood.

Design Stage 3.3: Technological Integrations for the Electronic Design

This phase focused on determining the choice of electronics, microcontroller, sensors, and key components, and how they should be integrated into the prototype. Due to cost and time constraints, the decision was made to use prefabricated spectral sensors to measure HR and SpO2. Novel algorithms are written to program these sensors. The complexity of measuring RR and FVC led the student researchers to custom design and build these sensors. The common method of measuring RR is a manual count and FVC is measured using medical-grade equipment, such as a spirometer. After researching the issue and reviewing relevant scientific principles, such as Ohm's Law, the student researchers determined that electrically conductive fabric could be designed to measure both biofunctions (Klein, 2024). Moreover, the use of spectral sensors and conductive fabric could also meet many of the project's engineering goal requirements such as UD compliance, low cost, and small scale. Additional research was conducted to determine how to optimize the durability of the conductive fabric. An epoxy form of graphene, an ultra-strong and lightweight nano-based material, was selected to possibly enhance the durability of the conductive fabric. Finally, artificial intelligence was integrated into the design to further enhance the prototype's ability to detect respiration.

Design Stage 3.4: Blending Traditional and Sustainable Energy Technology

The prototype is powered using a traditional 3.7V rechargeable lithium polymer battery, as well as mini photovoltaic cell panels. While the Li-Po battery serves as the prototype's main power source, the system of solar cells act as alternate power when the prototype is in direct sunlight. The objective is to prolong the life of the traditional battery and make the device more cost-effective.

Design Stage 3.5: Wearable Design

A key design feature of the prototype is that the electronics and sensors are integrated into a wearable garment. Traditional physiological sensors require straps, adhesive electrodes and a wired power supply. However, adhesive-based electrodes are difficult for many to use because the adhesives can cause skin damage and general discomfort (Holm, 2024 and Thyssen, 2010). To meet UD goals, the researchers opted to integrate the biofunction sensors into a wearable garment without any adhesives, thereby facilitating ease of use, low-effort, and adaptable options for a diversity of users.

Design Stage 3.6: Integrating Computer Networking

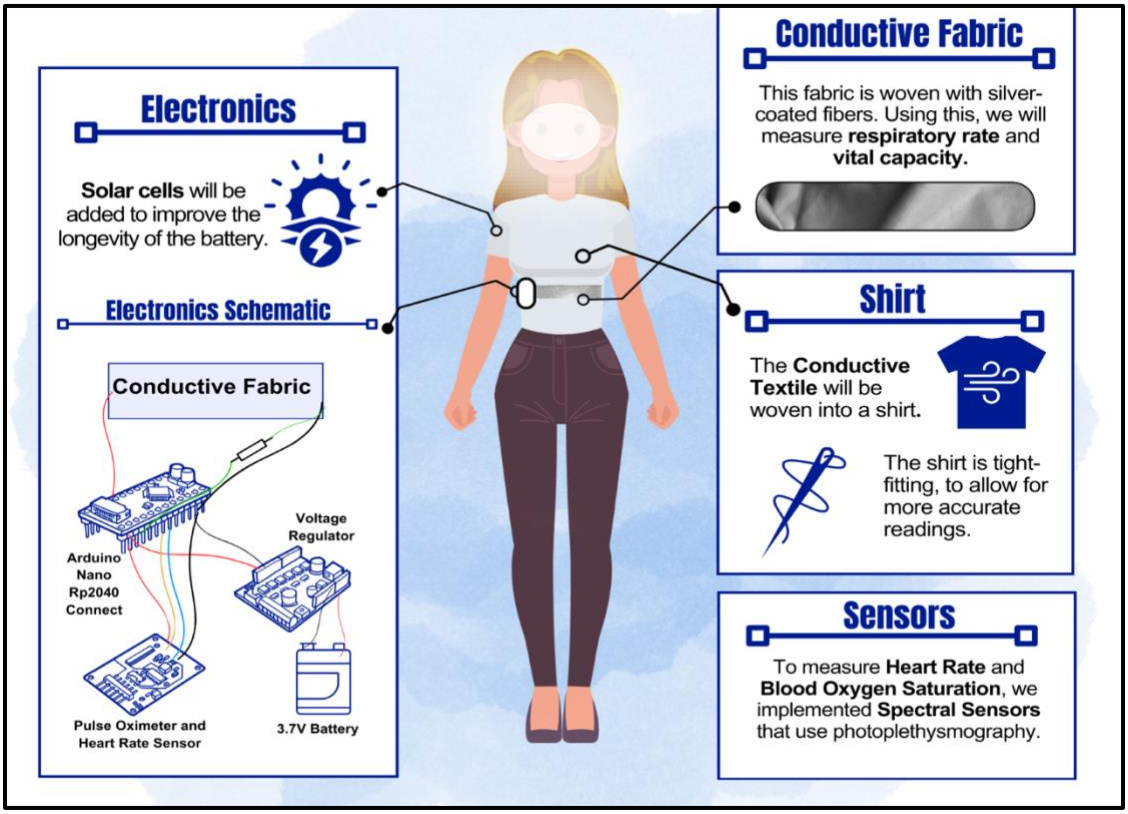
The next step in the design process involved developing a mobile app that used IoMT (Internet of Medical Things) connectivity for real-time streaming of biofunction data. This also enables users to control the prototype with their phone. It was decided that the app’s design should be fully UD compliant (ease of use, error tolerant, simple and intuitive), low-cost, and ensure user privacy To accomplish these goals, the mobile app must be designed to ensure users can operate it with minimal effort and technical skills, that key user features are customizable, that it must stream and store real-time data, and that the IoMT host must provide multiple layers of security.

Design Stage 3.7. Schematics

The last stage of the design phase included developing schematics that would serve as blueprints during the testing and iterations phases.

Figure 2

Design Schematic

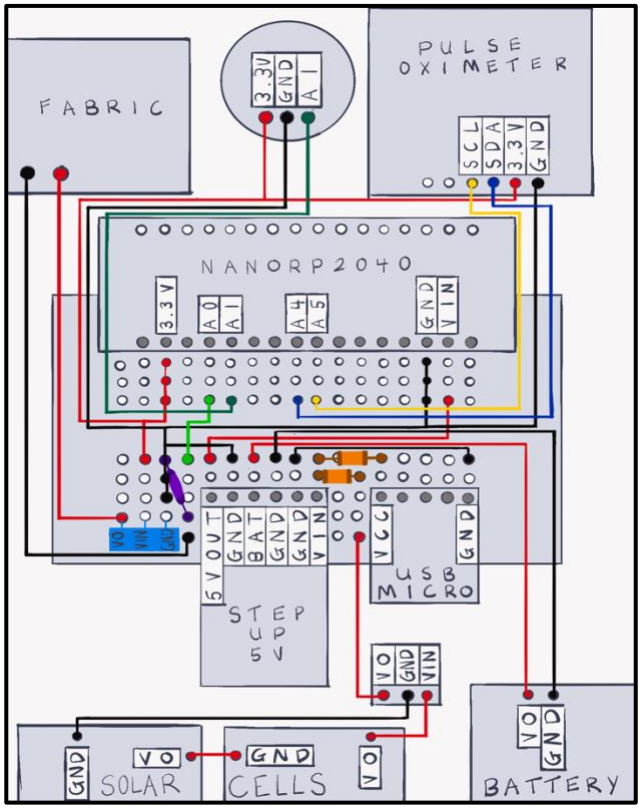


Schematic illustrating the key Prototype components (electronics, sensors, garment, and photovoltaic cell panels) and their placement on the prototype. Schematics designed by Student Researchers.

Figure 2 shows the first schematic, which is a detailed summary of the placement and interconnectedness of the electronics, biofunction sensors, and other core components. General parameters were determined for these features, such as size, processing speed, cost, WiFi capabilities, AI integration, and UD compliance. Finally, a wiring schematic was drawn. As shown in Figure 3, this labeled circuitry diagram serves as the blueprint for the electrical connections and components within the prototype made during the construction phase.

Figure 3

Wiring Schematic with labels



Wiring design for the Prototype's electronics.

Schematics by Student Researchers.

Design Stage 3.8. Materials and Equipment

During the design phase, a materials list was also developed to ensure that components could be on hand when needed during the construction phase. This helped to minimize interruptions in the project workflow. (Appendix E).

Phase 4: Prototype Construction

During this project phase, the prototype was constructed based on the schematics developed in Phase 3 and the engineering goals listed in Phase 2. The prototype was designed and constructed as a mid-fidelity device, intended to establish, and display the functionality of

integrated electronics (microcontroller and sensors) and evaluate the accuracy of the device's output. It was not intended to be a market-ready device or a medical/diagnostic device. However, it does demonstrate how the integration of advanced technologies can be used to accurately collect and analyze physiological functions data in a way that is portable, low cost, and widely accessible to populations with diverse needs. The prototype's construction took place in several stages with an emphasis on the actual build and on developing code to establish functionality and interactions.

Construction Stage 4.1. Develop Novel Algorithms

While listed as the first stage of the construction phase, coding took place throughout this phase as sensors and other components were added to the prototype. The code was written in C++. This language was used in order to ensure full compatibility with the Arduino Nano RP2040 Connect microcontroller. While some of the coding was customized from open-source code, most was written as novel algorithms. In particular, novel coding was developed for the microcontroller to a) instruct the Prototype's biosensors when to take measurements and b) develop unique respiration rate and forced vital capacity biofunction measurements c) transform the analog physiological function data it receives into biofunction output such as breaths per minute, and d) transmit output to the mobile app. Throughout the construction process (as well in post-testing iterations), these algorithms were modified to achieve increased sensor measurement accuracy.

Construction Stage 4.2. Electronics Engineering

The electronics consist of small prototyping boards and sensors to comply with Universal Design principles. These include the Arduino Nano RP2040 microcontroller, which also contains the Inertia Measurement Unit (IMU), a Sparkfun Spectral Sensor, a Sparkfun Pulse sensor, two voltage regulators, a 3.7 V Li-Po battery, and two flexible solar cells. The components were connected with wiring and a small, solderable breadboard. This core part of the project went through many iterations to create the optimal placement of components and adequate voltage.

For example, researchers tested the conductive fabric placement on various locations on the torso.

Construction Stage 4.3. Sensors and Materials Science

A key part of this phase was the construction of the biofunction sensors, which are used to measure human physiological functions, including respiration rate, heart rate, forced vital lung capacity, and blood oxygen saturation levels. The project team utilized advanced materials science and sensor technology to develop these sensors and then integrate them into the prototype.

Conductive Fabric Sensor

The key and most novel sensor was developed from electrically conductive textiles. These textiles are comprised of a fusion of commonly used fabric materials and advanced materials science technology. Conductive fabrics are made with metallic fibers that are electrically conductive, such as silver or copper, or with fibers that are coated with conductive materials. These textiles are strong, durable, flexible, and have a high heat resistance (Kiron, 2024). This sensor was developed to measure respiration rate (RR) and forced vital capacity (FVC) or lung capacity.

When a conductive fabric is stretched its electrical resistance (the opposite of electrical conductivity) may change. According to Ohm's Law, an increase in resistance in a circuit leads to a decrease in voltage (Klein, 2024). By measuring voltage changes across a piece of conductive fabric, the project team was able to calculate how much the voltage changes, which was converted into how much it was stretched (Kuphaldt, 2023). Several types of conductive fabric were evaluated for their elasticity, resistance, and durability. A voltmeter was used to test the fabrics' change in resistance (Table 1). The Armradield silver fiber knitted conductive fabric was selected based on its average change in voltage when stretched at 1 cm and 2 cm and because it returned quickly to its original shape. It is an anti-electrostatic fabric that is soft, lightweight, and sufficiently thick to be durable (Armadield, n.d).

Table 1

Comparison of electrically conductive fabric by elasticity

Fabric	Maximum Elasticity (cm)	Average Volts - Not Stretched	Average Volts - Stretched 1 cm	Average Volts - Stretched 2 cm	Average Change in Volts - Stretched 1 cm	Average Change in Volts - Stretched 2 cm
Amradield Conductive Silver Elastic Knitted	5	4.946	4.958	4.961	0.012	0.015
Shieldex Technik-tex P180 +B Knitted Silver	9	4.834	4.871	4.889	0.037	0.055
EMF Stretch with silver coated fiber	15	4.912	4.871	4.8	-0.041	-0.112

Table 1 shows the voltage of 3 conductive fabrics at rest and when stretched 1 cm and 2 cm. Table by Student Researchers.

The conductive fabric had to be precisely located on the wearable garment for it to produce the most accurate RR and FVC biofunction readings. RR is measured by counting the number of inhalations and exhalations per minute while FVC is captured by measuring the amount of a single chest expansion. A unique algorithm was coded into the microcontroller to capture analog voltage readings and convert them to a respiration rate measurement.

Spectral Sensors

The prototype uses spectral sensors to acquire heart rate (HR) and blood oxygen saturation (SpO2). To address cost and time constraints, two prefabricated sensors were used but were coded with custom algorithms. Unlike the smart fabric sensor that measures electrical resistance, these two spectral sensors use photoplethysmography (PPG) to measure HR and SpO2 functions (Park, 2022). To detect SpO2, the SparkFun AS7263 spectrometer was

selected for its low cost and compact size, measuring 4.5mm x 4.7mm x 2.5mm. It accurately measures the reflection of light in the blood with a photo detecting diode. A light-emitting diode flashes specific wavelengths of light reflecting off capillaries just under the skin of the wearer's finger (AMS, 2016). The SpO2 sensor detects the reflected light's color. A custom calculation was written to convert the analog signal of light absorbance to a blood oxygen saturation value. The sensor is located in a small case located on the user's left side, at waist level.

The prototype's heart rate sensor, a SparkFun Pulse Sensor Heart Rate Monitor, also uses photoplethysmography to measure this vital biofunction. The sensor is ultra-compact, measuring 0.625mm (diameter) x 0.125mm (height) with a vinyl cover to insulate the user from the circuit. The sensor was located on the user's left side at waist level and placed in a small soft case, which is attached to the garment. The sensor measures heart rate by detecting changes in blood color intensity to measure the user's heart rate. Novel algorithms were written to identify and analyze heart rate. First, the algorithm analyzes the analog signal emitted by the sensor to detect peaks in the signal. Second, additional equations were written to distinguish heart rate peaks from background noise. This second step was essential given that not all peaks represent heartbeats.

Inertia Measurement Sensor and Artificial Intelligence

The 6-axis Inertia Measurement Unit sensor (IMU), which was included as an integrated component of the Arduino Nano RP2040 Connect microcontroller to measure continual angular velocity and linear accelerations. This was used to determine specific motions of the prototype wearer. This was done by the student researchers who developed novel algorithms that were coded into the microcontroller through the Arduino IDE. These algorithms were written to identify discrete motions made by the prototype wearer, including when the user is still, walking, or running. The codes also enable the prototype to determine when fluctuations in the wearer's biofunctions may be attributable to changes in activity level as opposed to other physiological explanations.

Figure 4

IMU and AI Algorithms

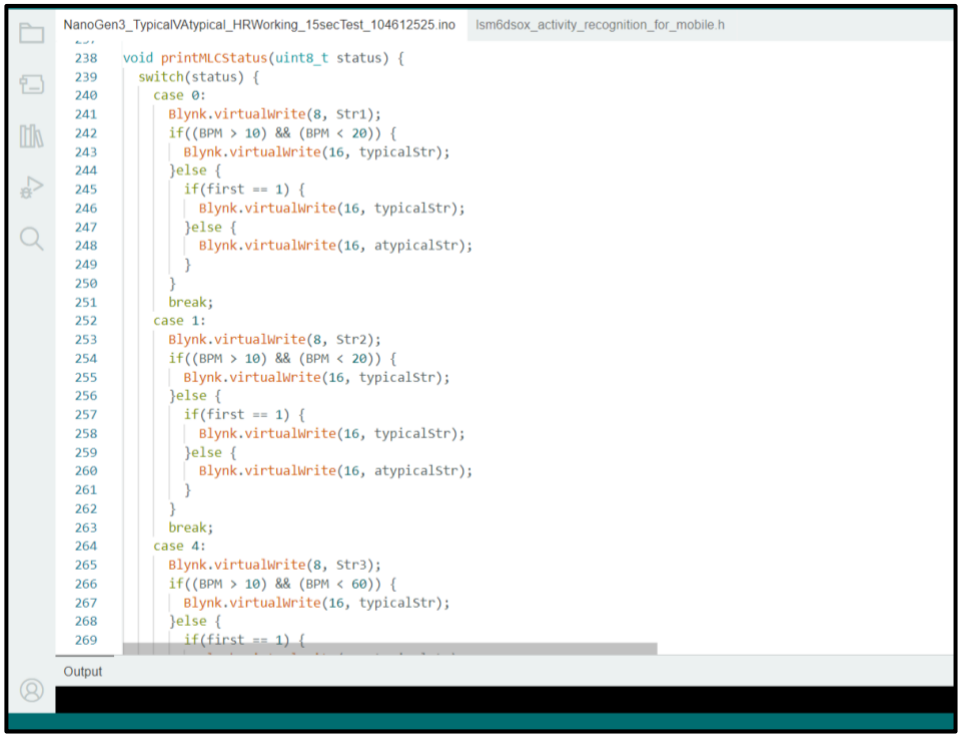


Image shows a code snippet that distinguishes between typical and atypical respiration patterns. Code & Image by Student Researcher.

The IMU is also constructed to be compliant with artificial intelligence. AI was used to identify even more complex motions made by the prototype's wearer. This enabled the prototype to distinguish between typical and atypical respiration (RR) patterns in the user. Novel algorithms were developed to measure the number of breaths per minute (bpm) of the user and compare this figure to the typical 12 to 20 bpm of an average adult (Cleveland Clinic, 2025). The BPM of an average adult may be customized based on key physical attributes such as age and body mass. Adding AI enhances the accuracy of the IMU's motion detection, expanding the detection ability to include additional motions like biking. Additional coding was written to expand the prototype's capacity for motion detection. This was essential to identify the

distinction between typical and atypical respiration occurrences. Because the microcontroller is coded to identify expanded physical motions based on acceleration and velocity, the student researchers developed additional algorithms that can attribute atypical respiration to motion intensity, such as exercising, as compared with atypical respiration not attributable to motion.

Construction Stage 4.4. Sustainable Energy

The prototype has two power sources. A traditional power source is a lithium polymer rechargeable battery pack (3.7V and a 2000mAh capacity). To enhance sustainability, two flexible, waterproof panels of photovoltaic cells measuring 95mm x 58mm x 1mm with a weight of 20 grams were attached to the sides of the shirt that houses the prototype (Figure 5). The goal of integrating this advanced energy technology into the Prototype is to improve the longevity of the device's power source, thereby enhancing its sustainability, which also helps in the project goal of UD compliance.

Figure 5

Photovoltaic Cell for sustainable energy

The photovoltaic cell panel that is integrated into the Prototype for more efficient energy use. Image by LSMSimmons.

Construction Stage 4.5. Integration into a Wearable Garment

` To meet the project goals the network of biosensors was integrated into a wearable garment, a tee shirt. The shirt is constructed of a soft nylon material with a close weave that retains its elasticity through repeated uses and washing/dry cycles. The electronics are housed in a small pocket on the lower left hem of the shirt. To ensure easy access and flexible use, the electronics can be easily detached from the garment to allow it to be washed and dried. The conductive fabric, which is sewn into the shirt, can be washed and dried along with the shirt.

Construction Stage 4.6. IDE and IoMT for Data Management, Display, and Transmission

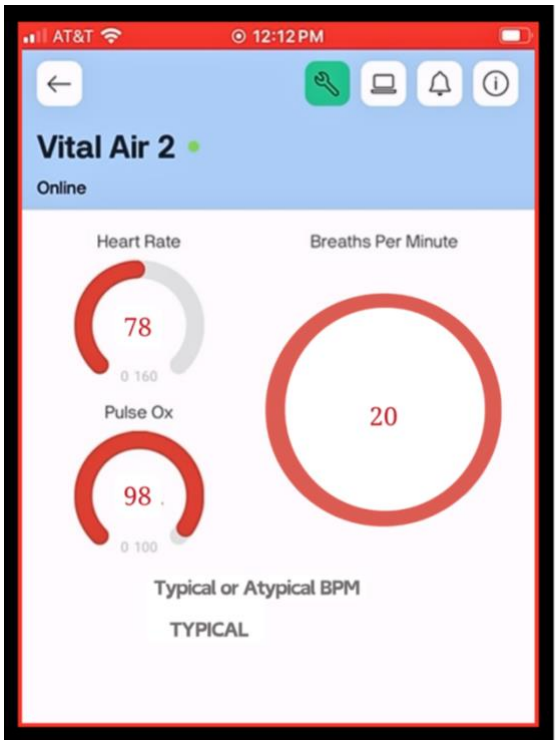
The project used *Blynk,* an Internet of Things platform, to build and host its mobile application because of its ease of use, attention to privacy and security, and the company's willingness to provide services at a deeply discounted rate. The app was developed for use in both iOS and Android mobile devices. It also has a web-based console that operates on desktop platforms running Windows, MacOS, and Linux. To start the process of constructing a mobile application, the Blynk library was integrated into the prototype code from the Arduino Integrated Development Environment (IDE). The library contains definitions for functions in the code that allow the project's prototype to communicate with the prototype app. The mobile application was designed using Blynk prefabricated widgets. The widgets were selected to display biofunction data in the most comprehensive manner and to ensure ease of use and flexible use. Widget options were chosen to ensure appropriate display contrast, color, and font size for users with diverse needs. The widgets on the app can be customized by the user for personalized needs.

The mobile application through the Blynk host (Figure 6) can transmit the biofunction data from the user to the recipient of the user's choice in real-time. Security is important when transmitting personal data, over the internet. *Blynk* uses industry-standard TLS (transport layer security) protocols when transmitting data. Transmissions are encrypted using "Let's Encrypt" certificates. "Let's Encrypt" is a non-profit company that provides free, open-source TLS/SSL

certificates. These certificates are used to encrypt internet-based communications. Access to the *Blynk* platform is through the secure HTTPS API (Blynk, 2024).

Figure 6

Prototype Mobile Application



The mobile dashboard displays real-time physiological data. Image by Student Researcher.

Construction Stage 4.7. Refuse Materials Disposal

All refuse materials, including electronics, batteries, and wires, were disposed of using local municipal recycling. Used and unused materials in good condition were retained for future use.

Phase 5: Testing and Iterations

Once the prototype was fully constructed, it was tested for performance and accuracy. Testing was conducted at the Mount St. Mary's University Anatomy Laboratory under the

supervision of the project's direct supervisors, a Mount St. Mary's University scientist, and a licensed physician's assistant. In addition, student researchers recorded observations about the prototype's UD features. A separate test was conducted to evaluate the usefulness of the graphene application to the conductive fabric.

Planning and Preparation

Prior to testing, there were several planning and preparation steps that were undertaken to determine the type and scope of testing and key objectives of testing and to ensure adherence to all governing regulations.

IRB and SRC Approval

As a first step in preparing for prototype testing, applications for permission to engage in human testing were written and submitted to the Mount St. Mary's University Institutional Review Board (IRB) since this was the planned testing site. The application was approved without the requirement of revisions. Next, a Science Review Committee (SRC) application was submitted to the Capital Area Science and Engineering Fair. The application was approved.

Testing Goals

Prototype testing was conducted for several reasons. First, a testing goal was to assess the functionality of the prototype's individual biofunction sensors and the prototype as a system of integrated sensors. In short, does the prototype and its sensors measure what they were designed to measure? A second goal of testing was to evaluate the accuracy of the device's individual sensors and the prototype as a whole. A final purpose of testing was to determine whether the prototype met its Universal Design requirements as identified in the project goals.

Scope of Testing

Prior to testing, the student researchers engaged in planning discussions with the project supervisors, the anatomy expert, and the medical expert to determine the scope and type of tests that would be conducted. While under ideal conditions, the prototype would have been tested using a large and randomized sample with multiple tests, this was not possible due to

time and testing constraints as discussed in Phase 2. Moreover, given that the prototype is a mid-fidelity device, extensive testing is not required. Alternatively, it was decided that the functionality, accuracy, and UD features of the prototype could be tested with the student researchers acting as test subjects. This limited scope of testing was determined to be acceptable given that the device is a mid-fidelity prototype (Traylor, 2024).

Type of Tests

Tests were conducted on the prototype to determine if it met the project goals. These tests provided useful information to identify areas in which the prototype's performance and accuracy needed to be improved during the iteration process (Canada, 2024).

1. *Prototype Test*. This test was used to evaluate the accuracy of the prototype's sensors in measuring vital functions. The prototype's measurements were compared to the measurement outputs of the commercial equipment.
2. *Graphene test*. This test evaluated the durability benefits of the graphene epoxy coating added to the conductive fabric. Graphene is a nanomaterial that is ultra-strong and lightweight (De La Fuente, n.d.).
3. *Usability Assessment*. Student researchers recorded direct observations about the prototype and mobile app's UD features while testing the device.

Testing

Two specific treatments were used to test the functionality and accuracy of the prototype. These consisted of one student researcher engaging in two physical activities, one low-intensity (sitting) and the other moderate-intensity (climbing stairs). The second student researcher recorded the prototype's output and test date and time.

In the first series of tests, the researchers assessed the prototype's accuracy by comparing measurement outputs from the prototype and from the commercial-grade equipment. The commercial equipment used in these tests included a BioPac Spirometer, BioPac ECG, and a Santamedical blood oxygen saturation meter (Appendix E) . The BioPac Spirometer

measured the test subject's forced vital lung capacity and the BioPac ECG measured heart rate (Figures 7 and 8).

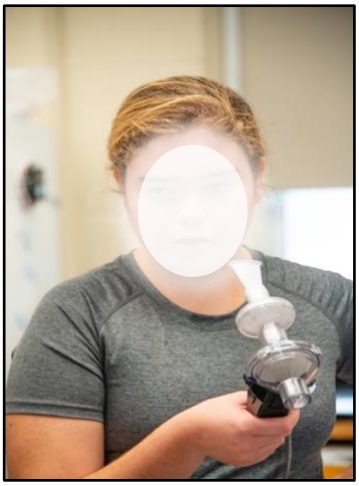
Figure 7

Preparing Spirometer

Research students calibrating the spirometer.

Figure 8

Spirometry Test



Research student testing FVC.

Images in both photos by LSMSimmons.

A Santamedical pulse oximeter measured blood oxygen saturation levels. A manual respiration rate was conducted by the licensed physician's assistant. This is a common method of measuring respiration (Johns Hopkins, 2022). During the testing, the second team member observed the test activities and recorded the prototype's vital signs readings.

In the second test, a student researcher wore the Prototype and ascended and descended a flight of stairs three times. After engaging in this test activity, the test subject's heart rate and respiration rate were measured using the commercial equipment and the prototype (Figures 9 and 10). SpO2 levels were measured by the commercial oximeter and with a manual count by the physician's assistant. These data were recorded by the second student researcher.

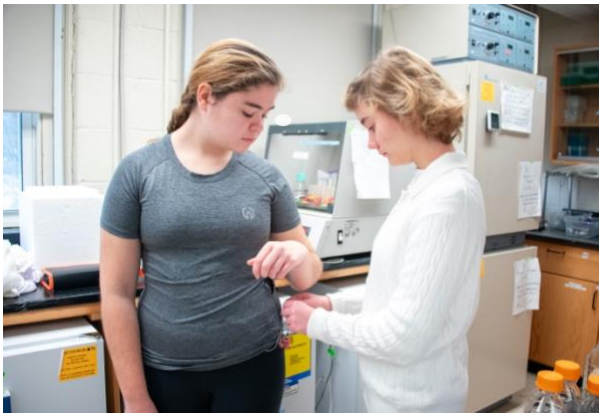
Figure 9

Climbing Stairs

Student researcher performs treatment during prototype testing. Image by LSMSimmons.

Figure 10

Prototype's SpO2 sensor



Student researchers adjust the Prototype's SpO2 sensor. Image by LSMSimmons.

Iterations

Testing showed that the prototype's FVC and RR measurement outputs were not sufficiently accurate. To optimize these functions, the equation used to calculate the forced vital air measurement was revised and the C++ code used to measure respiration rate was adjusted. Both of these are custom calculations specifically written to measure FVC and RR for this prototype.

Original Equation for FVC: 64.935 x volt Difference + 4.6429

Updated Equation for FVC: 27.871 x volt Difference + 1.7794

Adjustments were also made to the heart rate sensor. This change involved increasing the sampling rate. This entailed altering the frequency of data collection. When this iterations was made the sensor's accuracy improved.

Graphene Test

A graphene epoxy was applied to the conductive textile to determine if it would improve the durability of the fabric and protect the textile's conductivity, especially with washing. (Rohen, 2024). The conductive fabric coated in graphene and a control fabric (uncoated conductive fabric) were washed 20 times by hand using a commercial laundry detergent (Gain Original, HE). The fabrics were air dried on flat surface. After each washing and drying cycle, the strength of the coated test fabric and the control fabric was evaluated using a standard push-pull test (Kuphalt, 2023). A digital force gauge tensile strength meter was used to carry out this test (Figure 11). A tensile strength test measures the strength and elasticity of a fabric. The meter is attached to the fabric. The fabric is then pulled until a breaking point or until it reaches a pre-defined measurement point (Nelson Labs, 2023; McFadden, 2021).

Figure 11

Tensile Strength test

Student researcher testing tensile strength of fabric. Photo by LSMSimmons

The test fabric and the control fabric were visually observed after each washing and drying cycle. The fabric samples were then evaluated for pilling and tearing, both major and micro tears using an Andonstar AD249S-M Plus digital microscope with 2040x magnification displayed on a 10.1” high-resolution screen. Observations were recorded in a logbook and with digital photographs (Figure 12 and 13)

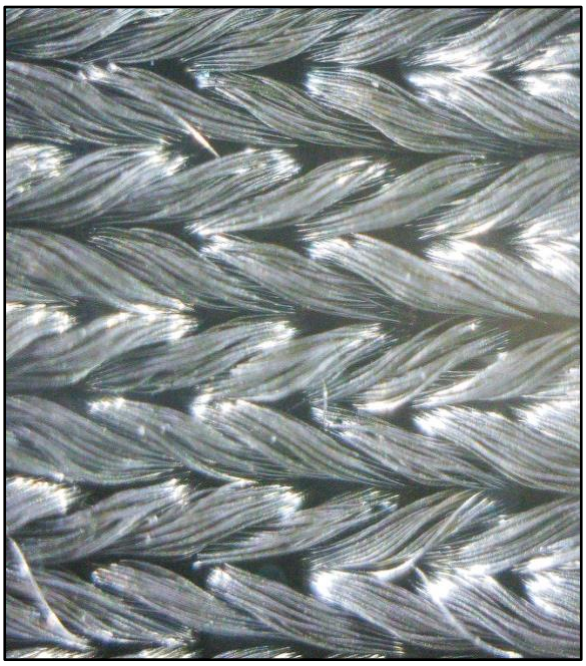
Figure 12

Graphene Coated conductive fabric

Graphene epoxy applied to conductive fabric at 2000x magnification.

Figure 13

Uncoated Conductive Fabric



Conductive e-textile without the Graphene epoxy at 2000x magnification.

Images by LSMSimmons

Usability Assessment

Both student researchers recorded observations made about the prototype during testing. The observations focused on three variables: comfort of the wearable garment, the

functionality, and the effort required to use the prototype during the testing process (Appendix F). In addition, the student wearing the garment was asked to draw a comparison between the prototype and the commercial instruments based on the same variables. The student researcher operating the mobile application recorded observations based on the effort required to operate the mobile application, to read the mobile app's controls, and the application's tolerance for error.

Phase 6: Findings and Analysis

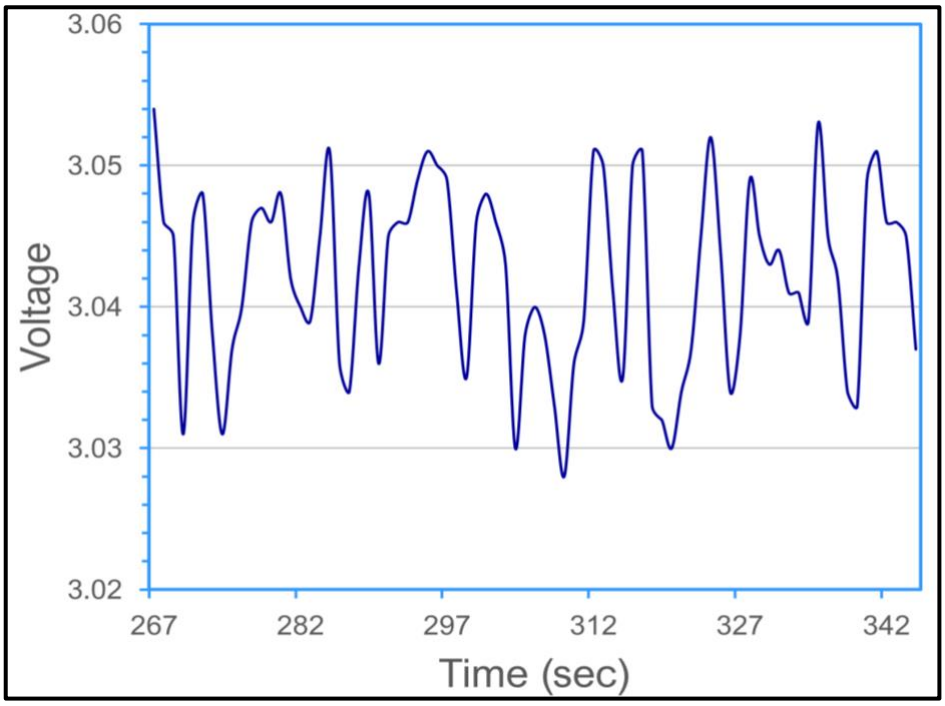
The testing process on the prototype showed that the device met the project's engineering goals. The prototype was designed and constructed using an integration of advanced materials, technologies, and techniques that successfully acquired and measured key biofunctions, heart rate, respiration rate, forced vital capacity, and blood oxygen saturation levels. Further, this biofunction sensor system is able to transmit vital signs data in real-time using Wi-Fi through a secure IoMT network. Moreover, the device was engineered using Universal Design Principles. The configuration of the prototype and mobile application are simple and intuitive. Finally, the prototype is designed for ease of use and flexible use by people with diverse abilities, needs, and backgrounds.

Sensor Findings

The sensor functionality test results confirmed that they measured the physiological function they were intended to measure. This is especially noteworthy for the respiration rate and forced vital capacity sensors since these sensors were uniquely designed using electrically conductive fabric and coded with novel algorithms. Figure 14 shows the prototype's respiration output, where a trough in the signal represents an inhalation, and a peak represents an exhalation.

Figure 14

Respiration Rate Output from Prototype



The chart shows the voltage output of the prototype during testing, indicating that the device obtains clear respiration patterns. Chart by Student Researcher

Similarly, the heart rate and blood oxygen saturation sensors on the prototype that are used to measure these two vital physiological functions produce results that are consistent with and meet project goals.

Device Comparison Findings

A Pearson-r analysis was used to evaluate the relationship between the prototype's vital physiological function measurements and those obtained from the commercial equipment. The Pearson-r test is a common way of identifying the linear relationship between variables. It measures the strength and direction of two variables. As seen in Table 2, all of the Pearson-r test results for all four of the project's biofunction variables range between <0.01 to 0.1 (Table

2). These values show that the prototype's accuracy was comparable to the commercial instruments used in these tests.

Table 2

Biofunction Comparisons by Instrument Type

Vital BioFunction	Prototype	Commercial	Pearson r	p-value
Respiration Rate (breaths per min)	16.0	17.3	0.99	$p < 0.05$
Forced Lung Capacity (liters)	2.46	2.51	0.66	$p < 0.05$
Blood Oxygen Saturation (% SpO2)	97.5%	98.5%	0.77	$p < 0.1$
Heart Rate (beats per min)	90.0	90.1	0.96	$p < 0.01$

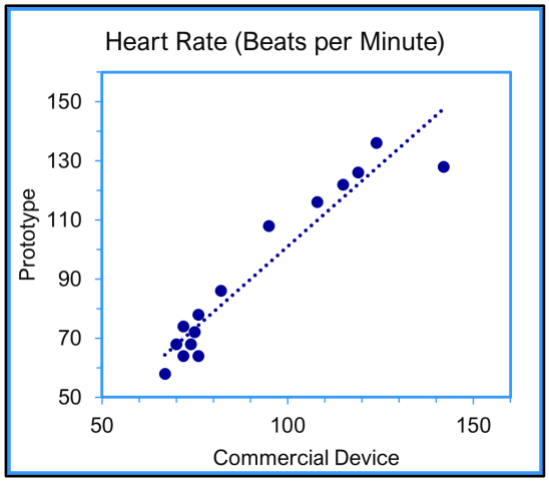
This table shows readings taken by the prototype and the commercial equipment and the manual respiration rate count, as well as the correlation between the two values. The table displays the results from the Pearson-r test as well as the p-value. Table by Student Researcher.

The charts in Figure 15 and Figure 16 compare the prototype's sensors with their corresponding commercial devices. The scatterplots in these figures illustrate that the heart rate variable and the forced vital capacity variable are statistically significant when compared to the heart rate and forced vital capacity measurements recorded during testing by the commercial BioPac spirometer and the BioPac ECG.

The scatterplot in Figure 15 shows the strong positive correlation between the outputs of the commercial device and the prototype as they measure heart rate. Similarly, Figure 16 shows a strong correlation between the forced vital capacity variable as measured by the BioPac Spirometer and the project prototype.

Figure 15

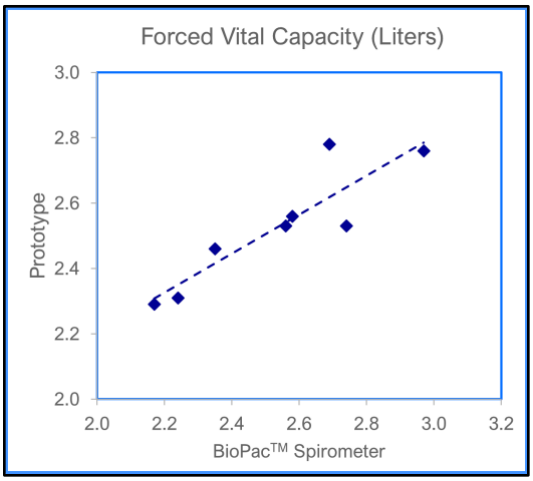
Prototype Heart Rate compared to Commercial Equipment



The chart shows the heart rate measurements taken by the prototype and the commercial equipment

Figure 16

Prototype Forced Vital Air compared to Commercial Equipment



The chart shows the Forced Vital Capacity measurements taken by the prototype and the commercial equipment

Charts by Student Researchers

Usability Assessment Findings

The observational assessment of the prototype and the mobile application indicated that the users found both to be easy to use. The prototype was observed to be comfortable to wear and required low effort to put on and remove. The assessment of the mobile application indicated that it required minimal knowledge and effort to operate. The observations noted that the design was simple and intuitive, allowing for ease of use in monitoring biofunctions. Even under the stress of repeatedly clicking, the app showed tolerance. It did not freeze or otherwise malfunction.

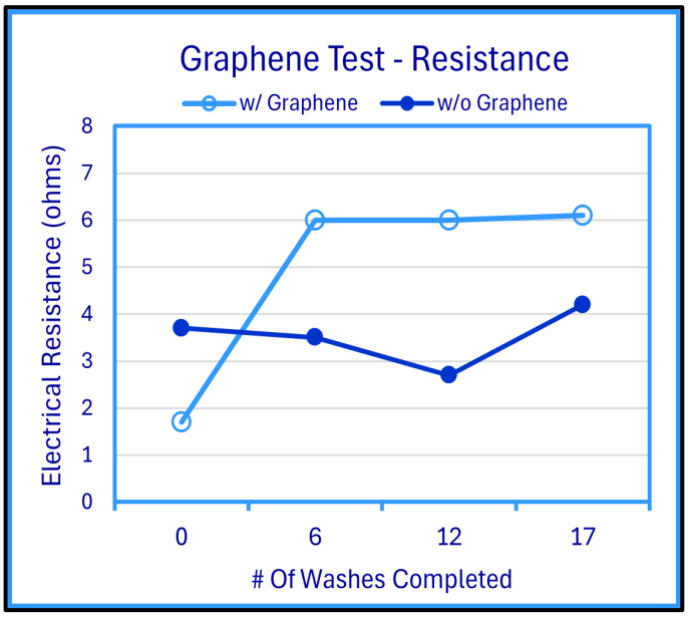
Graphene Findings

The graphene-coated textile saw an increase in resistance compared to the control

conductive textile. This is likely because the electricity flows through the graphene instead of the conductive fabric, which has a higher resistance, as seen in Figure 17. The graphene-coated textile also had a significantly higher tensile strength than the control. Because a lower tensile strength and resistance are more ideal for the prototype, it was concluded the graphene would not improve the prototype.

Figure 17

Graphene Findings



The chart shows the electrical resistance of the graphene after each wash/dry cycle and tensile test. Chart by Student Researchers.

Phase 7: Conclusions and Benefits

The findings and analysis show that the prototype meets the project goals. It accurately measures respiration data and patterns, forced vital capacity, heart rate, and blood oxygen saturation. The device determines the motion status of the user, calculates breaths per minute, differentiates typical and atypical respiration patterns, and displays data on a mobile and

computer application through IoMT connectivity. Moreover, testing observation notes from the student researchers indicated that the prototype was easy to use and comfortable to wear. The observations also stated that the prototype outperformed the commercial equipment in terms of user comfort and ease of use. The observations further showed that the mobile application was easy to use, required minimal effort to operate, and was tolerant of errors.

Reliability and Validity

Even though this was a mid-fidelity prototype, the very small participant sample size used for testing poses a threat to external validity. External validity refers to the ability to make generalizations about the project's outcomes. In addition, there is a threat to the project's internal validity due to the lack of diversity and randomization of the testing sample. One way to improve external and internal validity is to increase and diversify the testing participant sample (Nicolas, 2021).

Next Steps

There are several design modifications that can be implemented to improve the prototype's functionality, accuracy, durability, and validity.

Sensor Development

One possible modification that holds the potential to enhance the prototype's functionality is engineering a conductive textile replacement for ECG electrodes. The blood oxygen sensor is not as seamlessly integrated into the prototype as the other sensors. Improving this integration will improve both the functionality and ease of use. One issue that caused some problems during this project was short circuits in the boards, likely due to poor wiring connections. Using a custom printed circuit board will help stabilize these connections and improve functionality.

Currently, the prototype distinguishes between typical and atypical breaths per minute. However, this change cannot be attributed to a specific cause or possible category of causes, such as an environmental exposure or a physiological event. In the future, additional work on

the prototype's coding and components could be made to increase the sensitivity of the device to specific causes.

Durability Enhancements

The electronics lack sufficient durability to be worn for long periods of time and must be removed for washing. This hinders its simplicity and ease of use. One way to address this is to further explore the newly marketed conformal solutions such as parylene nanocoatings (Kisco, 2024). Another method or form of graphene could also be examined to enhance the durability of the conductive fabric.

Testing Improvements

While test results indicated that the prototype accurately measured key biofunctions, the testing outcomes are subject to validity threats due to the small testing sample size and lack of participant diversity. Expanding the testing process would improve the generalizability of the test findings. More concrete findings also establish a clear justification for moving the prototype from a mid-fidelity level to a high-fidelity level.

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Appendix A. IRB and SRC Documents: MSMU Institutional Review Board Approval Letter and CASEF SRC Approval Notification

MOUNT ST. MARY'S UNIVERSITY

Institutional Review Board
Office of the Provost
MountAspire@msmary.edu
301-447-5266

November 11, 2024

Dear Emma and Sarah,

The Mount St. Mary's University's Institutional Review Board has completed its Full Review of your submission, "Integrating E-Textiles, Nanotechnology, and AI to Enhance Physiological Data Acquisition" (FY25-23) and has **approved** your research project. You are free to commence your project and no further information is required by the IRB.

Several things to keep in mind as you conduct your project:

1) Approval is an ongoing process. If you modify your project in a way that adds risks or increases existing risks to human participants, you must submit a Substantial Change Notice to the IRB before implementing those modifications.
2) In addition, the Board must be notified of any unanticipated events that do or could affect the safety and welfare of the participants by submitting a Substantial Change Notice to the IRB.
3) Your project is approved for one year from the date of this notice. If your project is not completed by the end of the approval period, you will need to apply for a renewal (which is typically an Expedited Review). You will receive a reminder from the IRB one month before the end of the approval period. To avoid an interruption in your approval, please submit your renewal application two weeks before the end of the approval period to allow time for the review.
4) The principal researcher must retain all signed consent forms and documents for a minimum of three (3) years following the completion of the research project, or longer if judged necessary. For student research, the faculty research advisor must retain these documents.
5) The IRB reserves the right to, at any time, verify that the research is being conducted as described by observing procedures or by viewing consent forms or information collected.

If you have any additional questions, you can visit the IRB website or contact m.he@msmary.edu. We wish you the best with your project!

With Regards,

Dr. Minxuan He, Acting IRB Chair

From: **Valerie Knowles** director@casef.org
Subject: Re: Capital Area Science & Engineering Fair - CASEF SRC?
Date: December 3, 2024 at 10:14 AM
To: Lisa S McLeod-Simmons simmonsgroup@simmonsgroup.org

VK

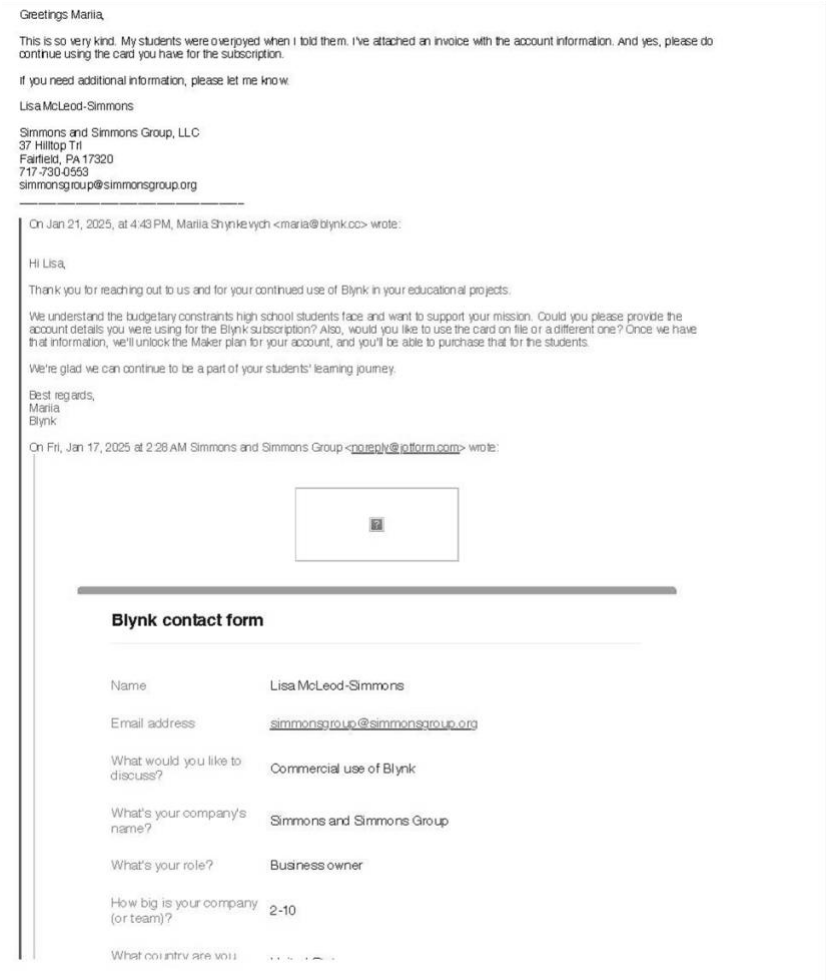
I have updated STEMWIZARD to reflect the approval.

Valerie Knowles, Fair Director
Capital Area Science and Engineering Fair Director, USPA01
501(c)3 EIN 23-2058835 PA BCO 35377
PA EITC Innovative Educational Program
WEB: www.casef.org
REGISTRATION: www.casef.stemwizard.com
YOUNG SCHOLAR REGISTRATION: www.casefys.stemwizard.com
MAILING ADDRESS:
103 Newport Road
Duncannon PA 17020

On 2024-12-03 10:03, STEM Wizard wrote:

> Greetings. Is it possible to get a status report on Emma and Sarah Simmons' request for CASEF SRC review of their proposed project, which is required in order for the students to move forward with the testing phase?
>
> STEM Wizard indicates that CASEF SRC has not decided yet about my team's research plan and forms. We have submitted the revised research plan, all forms that we were told were required (including the licensed medical professional Qualified Scientist form), the Abstract, and our Research Institution's signed IRB approval letter. The only outstanding form is ISEF 1C, which cannot be submitted until 'after' testing has been completed, per ISEF rules.
>
> If there is something else we need to do or if revisions need to be made, please let us know as soon as possible since tomorrow is the prior approval deadline.
>
> Thanks.
>
> Dr. McLeod-Simmons
>
> ---
>
> Lisa S. McLeod-Simmons, PhD
> 717-830-0553
> Simmonsgroup@simmonsgroup.org
> ---

Appendix B. Budget Constraints – Blynk Host Vendor



Greetings Mariia,

This is so very kind. My students were overjoyed when I told them. I've attached an invoice with the account information. And yes, please do continue using the card you have for the subscription.

If you need additional information, please let me know.

Lisa McLeod-Simmons

Simmons and Simmons Group, LLC
37 Hilltop Trl
Fairfield, PA 17320
717-730-0553
simmonsgroup@simmonsgroup.org

On Jan 21, 2025, at 4:43 PM, Mariia Shynkevych <maria@blynk.cc> wrote:

Hi Lisa,

Thank you for reaching out to us and for your continued use of Blynk in your educational projects.

We understand the budgetary constraints high school students face and want to support your mission. Could you please provide the account details you were using for the Blynk subscription? Also, would you like to use the card on file or a different one? Once we have that information, we'll unlock the Maker plan for your account, and you'll be able to purchase that for the students.

We're glad we can continue to be a part of your students' learning journey.

Best regards,
Mariia
Blynk

On Fri, Jan 17, 2025 at 2:28 AM Simmons and Simmons Group <noreply@iotform.com> wrote:

Blynk contact form

Name	Lisa McLeod-Simmons
Email address	simmonsgroup@simmonsgroup.org
What would you like to discuss?	Commercial use of Blynk
What's your company's name?	Simmons and Simmons Group
What's your role?	Business owner
How big is your company (or team)?	2-10
What country are you from?	United States
Which category describes your product best?	Bioengineering prototyping
Tell us what you are building and how we can help you	I am working with a group of high school students who are the process of completing a project in the field of bioengineering. They had the "maker" plan, which is no longer available. Do you have an education plan available? Or is it possible to extend their current "Maker" plan for several months? They do not have the funding for the "Pro" plan. Thanks. Dr. McLeod-Simmons

https://blynk.io/

https://blynk.io/contact-us-business?header

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Mariia Shynkevych
Marketing Director at Blynk
https://blynk.io/

Appendix C. Project Division of Labor

Table 3

Project Division of Labor

Student Researcher 1	Background research on Telemedicine
	Research on FVC and RR
	Design of FVC and RR sensors
	Research on wearable biofunction sensors
	Wrote novel algorithms for biofunction sensors
	Wiring Circuitry Design
	FVC and RR data analysis
	Recorded data from mobile app during testing
Student Researcher 2	Background research on Conductive Fabric and Graphene
	Conductive Fabric selection
	Integration of conductive fabric into wearable garment
	Circuitry connections
	Soldering
	Integrated heart rate monitor into prototype
	Heart monitor data analysis
	Graphene testing and analysis
	Subject for prototype testing
Shared	General Schematic design development
	Designed Testing protocols
	Developed Risk assessment plan
	Designed mobile application
	Research paper writing and editing

Appendix D. Safety Constraints - Risks and Risk Mitigation

1. Fabric-related Dermatitis and Hypersensitivity. Epidermal allergic reaction to conductive textile material, which consists of an electrically conductive metal.
    - The conductive textiles used in this study are embedded with silver, which poses a relatively low risk of contact dermatitis compared to other metals like nickel (Cleveland Clinic, 2024, July 3).
    - There will be a layer of cotton or nylon fabric between participants' skin and the conductive textile, except for the biosensors which will be no larger than 6 square centimeters in area.
2. Exercise-induced respiratory distress. Since a student researcher will engage in a test treatment that includes moderate intensity exercise, respiratory distress is a possible risk.
    - The test subject will not be permitted to engage in the test if there are any signs of respiratory illness.
    - The testing will be halted if the subject exhibits any signs of respiratory distress.
    - An adult who is in CPR and first aid will be present during the testing.
    - The testing will be held at a facility that has an on-site health clinic within 0.25 miles.
3. Slipping, tripping, or falling during the trials. Because one of the test treatments includes a physical activity, climbing stairs, there is a risk of slipping or falling during the testing process.
    - Obstacles that may cause slipping, tripping, or falling will be cleared from the test location.
    - Test subject will be requested to wear rubber-soled shoes to reduce slipping.
    - Test subject will be instructed to use the handrail that is located along the staircase.
4. Solder Fume Irritants. Solder flux containing rosin (also called colophony), generates visible fumes. Rosin exposure can cause upper respiratory track and eye irritation.

- Safety glasses will be worn while soldering or when near someone who is soldering to protect eyes from direct contact fumes.
- Soldering will be done in a well-ventilated area.
- The minimum amount of solder flux will be used to complete the task.
- Prolonged use and exposure to solder flux will be avoided.

5. Electrical Hazards. Because the prototype includes electrical wiring and 9V lithium and LiPo batteries, there may be a risk of superficial shock if a student researcher comes into contact with a damaged battery or ungrounded wiring.
    - Student researchers and the adult project supervisors (teachers) will check all batteries, wires, electrical circuits, and electrical components to ensure that none are damaged. Any damaged materials will be removed and replaced with new components.
    - All electrical wires and connections will be properly insulated. All wiring used in this project will be manufacturer-insulated wiring.
6. Thermal Burns. Skin burns can result from using a soldering instrument. Soldering instruments can reach up to 400°F.
    - Since air pockets or impurities can pop and scatter solder, safety glasses will be used to protect eyes and safety ‘heat’ gloves to protect hands.
    - The soldering iron is placed in its stand when not in use.
    - The soldering instrument will be unplugged, cooled, and stored in accordance with the manufacturer’s recommendations when not in use.

Appendix E. Component and Equipment Tables

Table 4

Major Component List

Electronics	**Sensors & Sensor accessories**	**Power Source**	**Accessories**
Arduino Nano RP2040 Connect	Sparkfun Spectral Sensor Breakout AS7263 NIR (Near Infrared)	3.7V Li-Po Battery	Under Armour Spandex and Polyester long-sleeved T-shirt
Mini Solderable Breadboard	Sparkfun Spectral Heart Rate Monitor	Comidox 5V step up converter	Stainless Steel Snaps
47-ohm resistor	Amradield brand conductive fabric, woven silver coated fibers	Flexible Solar Panel Mini Thin Film Solar Cell Battery Charger 2V 0.5W (195mm x 58mm x 1mm)	Binneker 28 Gauge PVC 1007 Solid Electric Wire Red 50 ft 28 AWG 1007
2 diodes	Graphene - Flexible silver / graphene conductive epoxy g6e-fxsg	2A 5V Charge Discharge Integrated Module 3.7V 4.2V for 18650 Lithium Battery Charging Boost Mobile Power Protection PCB Bd	MG Chemicals (422B-340G) silicone conformal spray
USB micro connector module		3.3V voltage regulator	

Table 5

Major Equipment List

Spirometer/ECG System (MSMU) BioPac BLS4 system with MP36/MP35 with Exercise Physiology Biomechanics Transducer Pack	**Digital Microscope (Personal)** Andonstar AD249S-M Plus 10.1" HDMI Soldering Digital Microscope, 2040x 3 Lens 2160P UHD Video Record
Blood Oxygen Meter (Personal) Santamedical Generation 2 SM-165 Fingertip Pulse Oximeter Oximetry Blood Oxygen Saturation Monitor	**Desktop Computer (Personal)** MacBook Pro, 16”2.4 GHz, 8-Core Intel Core i9. macOS Sequoia 15.3. Intel UHD Graphics 630 1536 MB, 7 TB storage
Smartphone (Personal) Apple iPhone 15 Pro Max, MU683LL/A. iOS 18.3.1, 256GB storage	**Digital Multimeter (Personal)** AstroAI DM6000AR True-RMS Multimeter 6000 Counts, Ohmmeter Auto-Ranging Tester
Tensile Strength Meter (Personal) Digital Force Gauge Push and Pull Meter Dynamometer Tension Pressure Tester Thrust Meter Compression Load Plug Force Destructive Tests	**Soldering Iron (Personal)** Soldering Iron Kit, 90W 110V LED Digital Soldering Iron with Ceramic Heater, Adjustable Temperature Soldering Welding Iron, various tips

Appendix F. Usability Assessment

Part I: This section should be used by the project's student researcher wearing the prototype to evaluate the device's universal design features.

Instructions: Consider the following design features when testing the prototype.

1. Level of effort required to put on the prototype garment.
2. Level of comfort when wearing the prototype
3. Level of effort required to use the SpO2 biofunction sensor.
4. Compare the prototype and the commercial equipment in terms of:
    a. Comfort
    b. Ease of Use
    c. Effort required for testing

Part II. This section should be used by the student researcher operating the mobile application during testing to evaluate the device's universal design features.

Instructions: Consider the following design features when testing the prototype.

1. Effort required to operate the mobile application
2. Effort required to read the controls of the mobile application.
3. App tolerance to error.