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MEMS 411: Smart Shirt Electronics Housing

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SMART SHIRT ELECTRONICS HOUSING

Millions of Americans suffer from sleep apnea, a chronic condition that can impact the quality of sleep and livelihood of those impacted by it. The sleep tests that are performed to see if a patient has sleep apnea are very invasive to those that undergo them, but the WUSTL Smart Shirt removes the need for such tests. This biometric shirt contains electrodes that measure blood pressure, heart rates, and EKG diagnostics that create reports to determine if the patient has sleep apnea, removing the need for the invasive sleep tests for a diagnosis.

We were tasked with making the electronics and battery housing in the WUSTL Smart Shirt have a smaller profile and be more comfortable for the wearer of the shirt. Additionally, we were tasked with replacing the electronic connections on the shirt to make the connection between the shirt and the electronics more reliable.

After creating more than ten different prototypes, we were able to meet all the design goals in our final design. The main electronics housing was made of flexible Ninjaflex TPU material to increase the comfort of the shirt for the wearer and increase the housing's resistance to sweat. The battery housing was incorporated into the lid of the electronics housing to reduce the number of mechanisms in the system and to prevent the batteries from being in contact with the wearer of the shirt. Finally, the electronics connection was fixed by creating a connection that would be sewn into the shirt and connect to the electronics of the housing using an audio jack.

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1 Introduction

Approximately 18 million Americans are plagued by sleep apnea, a potentially life-threatening condition where those affected temporarily stop breathing as they sleep. This accounts for nearly 6.62% of the United States population. To determine a treatment plan, patients often must undergo sleep studies. These tests measure key health attributes such as heart rate, blood pressure, and EKG. For most, sleep studies are bothersome and sometimes unnecessary in milder cases.

Recently, developments have been made in "smart shirts" that utilize conductive fibers to transmit signals in a wireless format. Washington University in St. Louis is among the participants. This project seeks a comfortable, low-profile housing for a battery and supplementary electrical components that can be connected to the smart shirt. If completed successfully, wearers can determine the status of their condition from the comfort of their own homes and determine whether a proper sleep study will be required.

2 Problem Understanding

2.1 Existing Devices

The Hexoskin Smart Shirt is the closest competitor to the WUSTL Smart Shirt and has streamlined many of the features that are present in our prototype.

2.1.1 Existing Device #1: Hexoskin Smart Shirt

Figure 1: Hexoskin Smart Shirt

Link: https://www.hexoskin.com/products/hexoskin-shirt-men

Description: The Hexoskin Shirt provides continuous measurements of cardio-pulmonary activity and sleep data using conductive textile sensors. It is designed to be comfortable and machine-washable. The electronics are low-profile and located on the right side of the shirt. Data is transmitted via Bluetooth.

2.1.2 Existing Device #2: WUSTL Smart Shirt Current Case Prototype

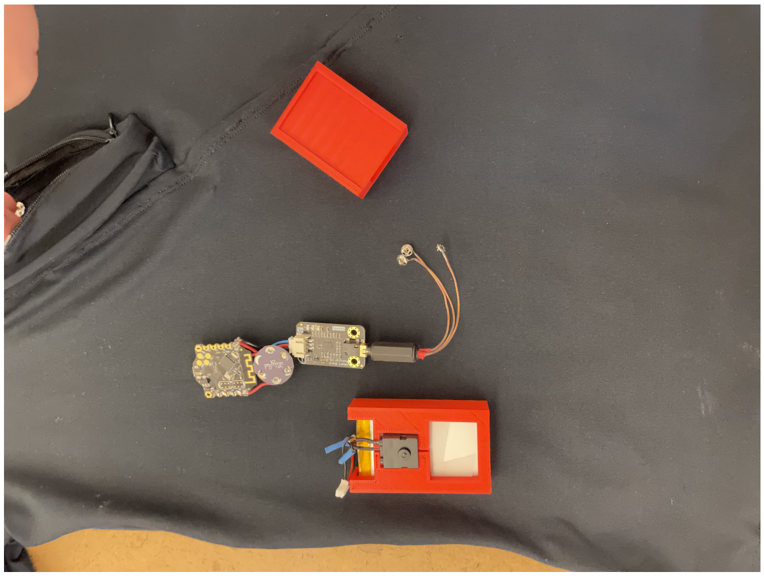


Figure 2: Current Prototype

Link: https://samfoxschool.wustl.edu/people/faculty/66-mary-ruppert-stroescu
Description: The current prototype of the shirt has a zipper pouch that holds the 3D-printed electronics housing and battery pack inside. The electronics are connected to the conductive threading via electrical snaps located underneath the battery housing. Currently, these connections do not provide a stable connection to the shirt as they frequently become disconnected, which can ruin the results of the tests being done for the wearer of the shirt. The red housings made of 3D-Printed PLA material are also very clunky and are uncomfortable for the user, so the comfort of the electronics needs to be improved.

2.1.3 Existing Device #3: MIT Electronic Textile Conformable Suit (E-TeCS)

Figure 3: MIT E-TeCS Battery Connection

Link: https://news.mit.edu/2020/sensors-monitor-vital-signs-0423
Description: The MIT Electronic Textile Conformable Suit (E-TeCS) is a shirt that is very similar to ours in that it measures heart rates, respiration, body temperature, and other biometrics of the person wearing the shirt. It has a very small battery pack and electronics center located on the side of the shirt. It can also connect to devices remotely so that the results can be seen in real-time.

2.2 Patents

2.2.1 Washable Intelligent Garment and Components - Patent WO2013134856A1

This patent was created by CARRE TECHNOLOGIES Inc.for a garment that contains electrical wiring and technology very similar to the WUSTL Smart Shirt. This patent specifically covers the ability of the shirt to be washed by the user without affecting the electronics of the shirt. The claim of this patent is that this shirt differs from other wearable technology in that it has sensors throughout the shirt whereas other shirts only have sensors in specified areas. This patent is unique in that the shirt can be washed with all these sensors incorporated everywhere.

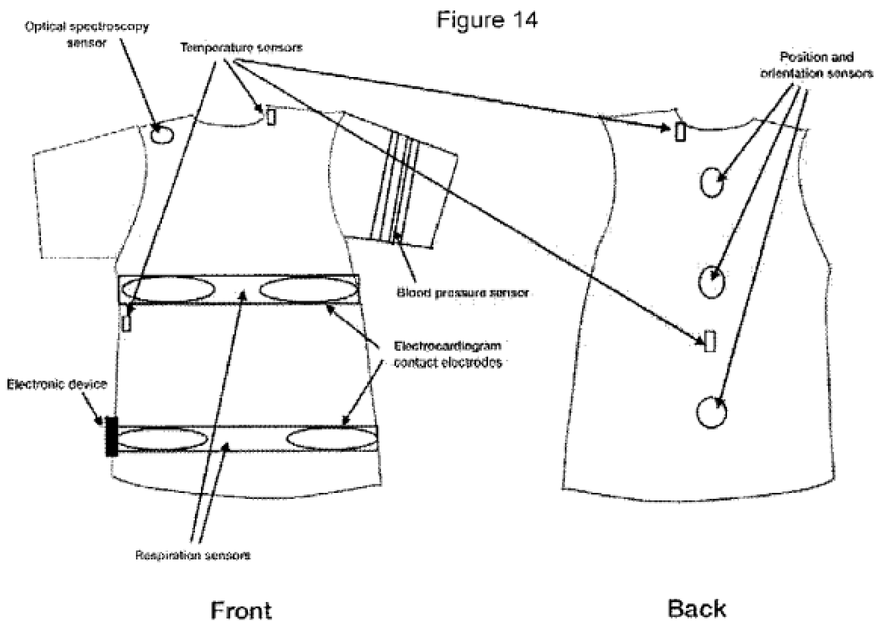


Figure 4: Patent Images for the CARRE TECHNOLOGIES Intelligent Garment

2.2.2 Washable Intelligent Garment Electronics Case - Patent USD921905S1

This patent covers the box containing all the electronics of the CARRE TECHNOLOGIES Washable Intelligent Garment mentioned above. This patent describes that this case has a unique connection that allows the electronics to connect to the shirt effortlessly and without any disruption to the medical information collected by the shirt. It is also waterproof so that it can be washed with the garment.

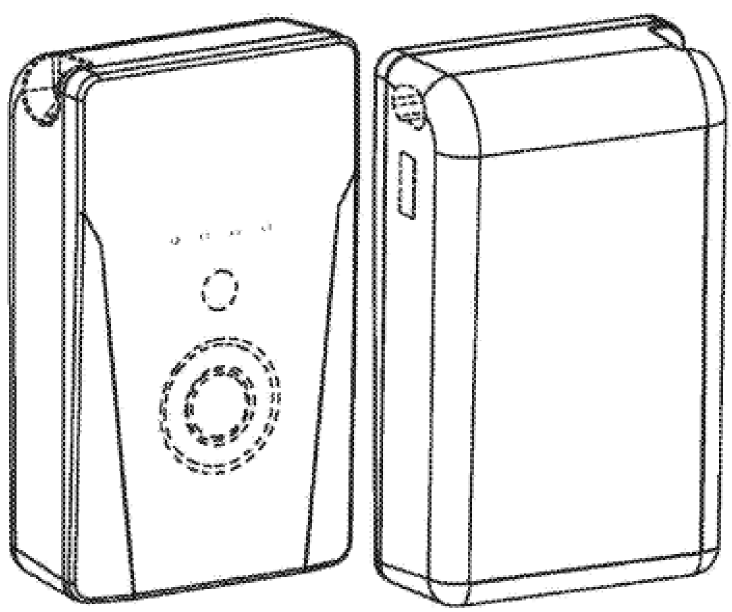


Figure 5: Patent Images for CARRE TECHNOLOGIES Garment Case

2.3 Codes & Standards

2.3.1 The Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances Testing (UL 94)

This standard outlines classifications for the flammability of plastic materials as well as their behaviors as heat is applied. The classifications for the plastic materials are HB, V-2, V-1, V-0, 5VB, and 5VA, where HB is the least flame-retardant and 5VA is the most flame-retardant. Since the batteries and electronics we are working with will likely not dissipate large amounts of heat, we will aim to use a plastic that is less flame-retardant as this will be cheaper. However, the less flame-retardant plastics will likely need to be thicker to meet the UL-94 standards, so we will need to find a plastic material that accomplishes our goal while maintaining cost efficiency and lighter weight.

2.3.2 The Standard for the Safety of Household and Commercial Batteries (UL 2054)

This standard outlines many safety features that many kinds of batteries (alklaine, lithium-ion, button cell, NiCd, etc.) must possess in order to be certified by UL. Some of the safety features the batteries must posses are safeguards from short circuits, environmental effects, and overcharging. This will be an important code to follow since we must make sure that the batteries used do not harm the user of the shirt.

2.4 User Needs

The shirt must be comfortable enough to sleep in, so the casing for the electronics shall be as ergonomic as possible. It needs to be located equidistant to the electrodes inside the shirt. The current snap design does not provide a consistent connection; more reliable connections to the conductive threads must be included.

2.4.1 Customer Interview

Interviewee: Professor Mary Ruppert-Stroescu
Location: Bixby 15, Washington University in St. Louis, Danforth Campus
Date: September 8^{th}, 2023
Setting: Introduced was the context of the problem, as well as the current smart shirt design. Advancements in conductive threads were also discussed. The current battery housing was inspected in greater detail, and participating groups were notified about the problems that arose from this design. The interview lasted approximately 30-45 minutes.
Interview Notes:
Describe the current electrical connections on this device.

- Electrical connections are made via snaps, which tend to be noisy during movement. A quieter design is preferred.

How is the device used?

- Users must sleep on their backs for ideal connections and comfort with the battery pack loaded. Modifications will occur only to the electronics housing, and not the shirt itself.

How are measurements taken?

– Electrical signals are measured via three electrodes located equidistant to the battery housing. Conductivity is increased with the user's sweat as they sleep.

What are the dimensions of the current prototype?

– Dimensions are located in a Google Drive folder. These will be provided at a later time.

What are some additional goals for this new design?

– As the shirt is machine-washable, the electronics housing must be removed before cleaning. Though not required, a goal is to design a waterproof housing that can remain inside the shirt during washing.

2.4.2 Interpreted User Needs

The customer has several needs that she has had issues with in her current prototype as they are listed below. They are all of high importance as she has been able to create a working prototype that accomplishes the end goal of capturing medical information, we just need to make the battery pack and electronics more comfortable for anyone who wears the smart shirt.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The battery pack is comfortable	5
2	The battery pack is lightweight	5
3	The battery pack remains fixed in the same spot	4
4	The electrical connections between the shirt and the battery remain attached when connected	5
5	The battery pack is waterproof to prevent sweat or other liquids from damaging the electronics	3

Note: Importance ratings range from 1 to 5, with 5 representing the greatest significance.

2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total weight	g	25	20
2	1	Total volume	cm^3	45	42
3	2	Rating of "comfort" by focus group	avg. score	$> 6/10$	$> 8/10$
4	4	Ease of connection (Mechanical and Electrical)	avg. score	$> 6/10$	$> 8/10$
5	5	Total length of the electronics	cm	11	10
6	5	Total width of the electronics	cm	4	3.5
7	5	Total height of the electronics	cm	26	21

3 Concept Generation

3.1 Mockup Prototype

Figure 6: Front view of mockup prototype with open lid

Figure 7: Side view of mockup prototype

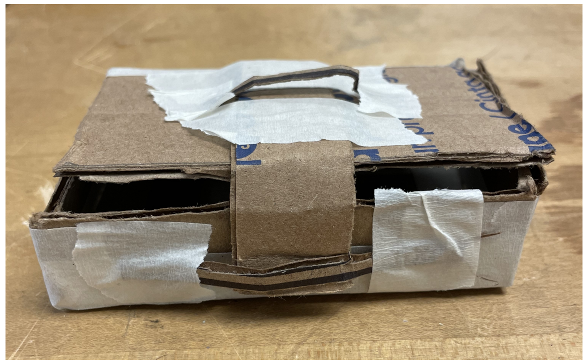


Figure 8: Additional front view of mockup prototype with closed lid

The mockup prototyping process highlighted some of the practical design aspects that would be required for the completed product. Some of these include providing a mechanism for opening and closing the electrical housing, as displayed in the above figures. It is clear that a significant portion of the design process will center around the device being opened and closed, leaving much room for creative flexibility. The primary goal for this device is to be comfortable and low-profile, so this mechanism must not be intrusive or bulky compared to the rest of the enclosure. However, the device must be secured enough to prevent opening during normal movements by the wearer as they sleep.

3.2 Functional Decomposition

One of the earliest steps that has been taken to find a suitable design is to create a function tree for the battery pack. This outlines all of the functions that the battery pack must possess so that it can be functional and user-friendly. A few examples of these functions are shown in the function tree below.

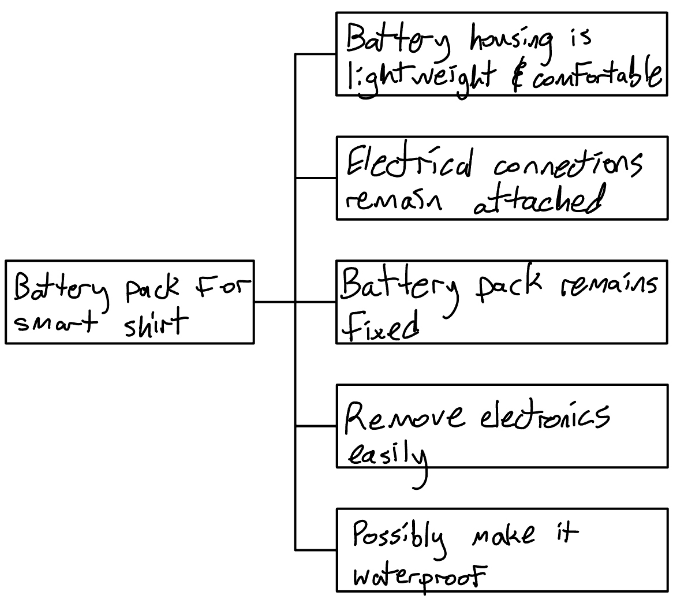


Figure 9: Function tree for the Battery Pack.

3.3 Morphological Chart

Based on the highlighted sub-functions, some of the device's subsystems can be theorized for the final conceptual designs. Many ideas are presented in the morphological chart below.

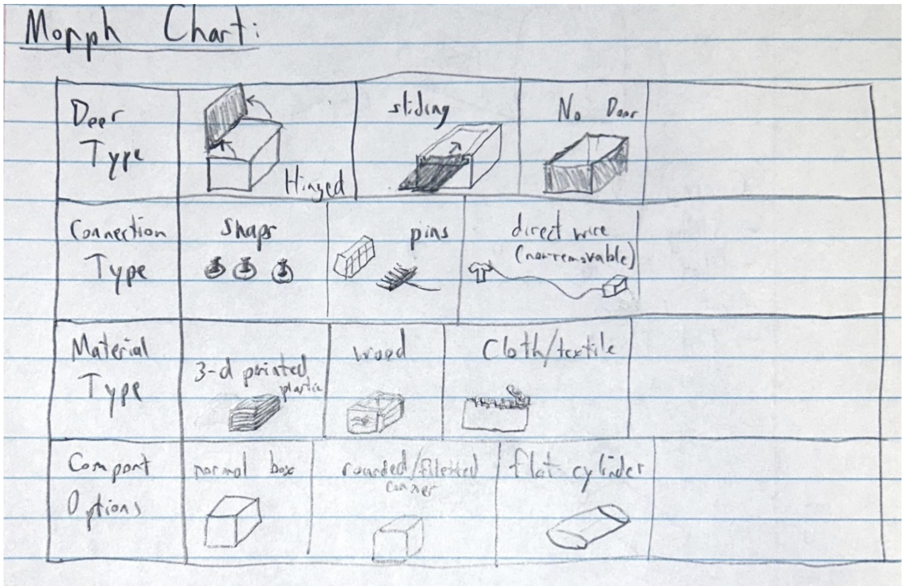


Figure 10: Morphological Chart for the Battery Pack.

3.4 Alternative Design Concepts

3.4.1 Concept #1: Everything Together

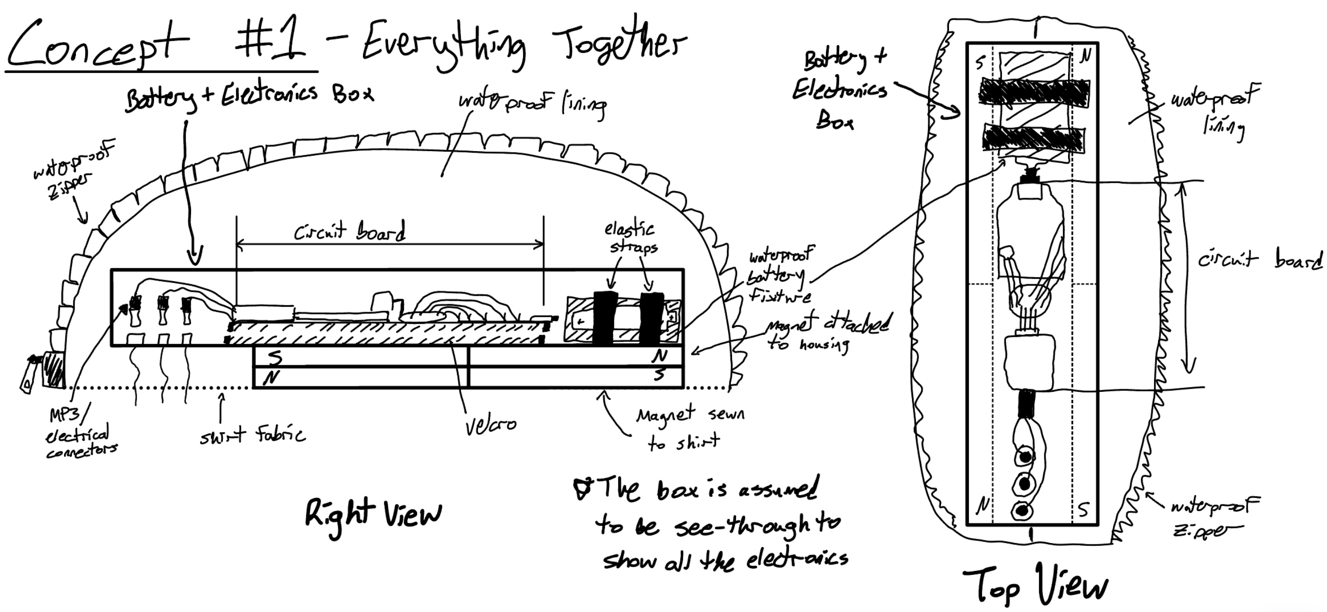


Figure 11: Sketches of the combined ideas concept

Description: The battery and electronics box hold the batteries and all of the electronics together in a fixed position. All of the electrical pieces are held together in a variety of ways. The main electronics have a thin side of velcro on their base, which connects to the other velcro side attached to the bottom of the box. The battery pack is held in place by elastic straps, which allow for easy removal to replace the batteries while keeping them fixed in the same spot. The electronics are connected to the shirt using MP3 electrical connectors, which are very robust and prevent the connections from becoming undone. The entire box system is held in place on the shirt by magnets, which allow for easy removal of the electronics box to launder the shirt. The pouch that seals the electronics from outside effects is lined with a waterproof lining and a waterproof zipper to prevent things like sweat from damaging the electronics.

3.4.2 Concept #2: Velcromania

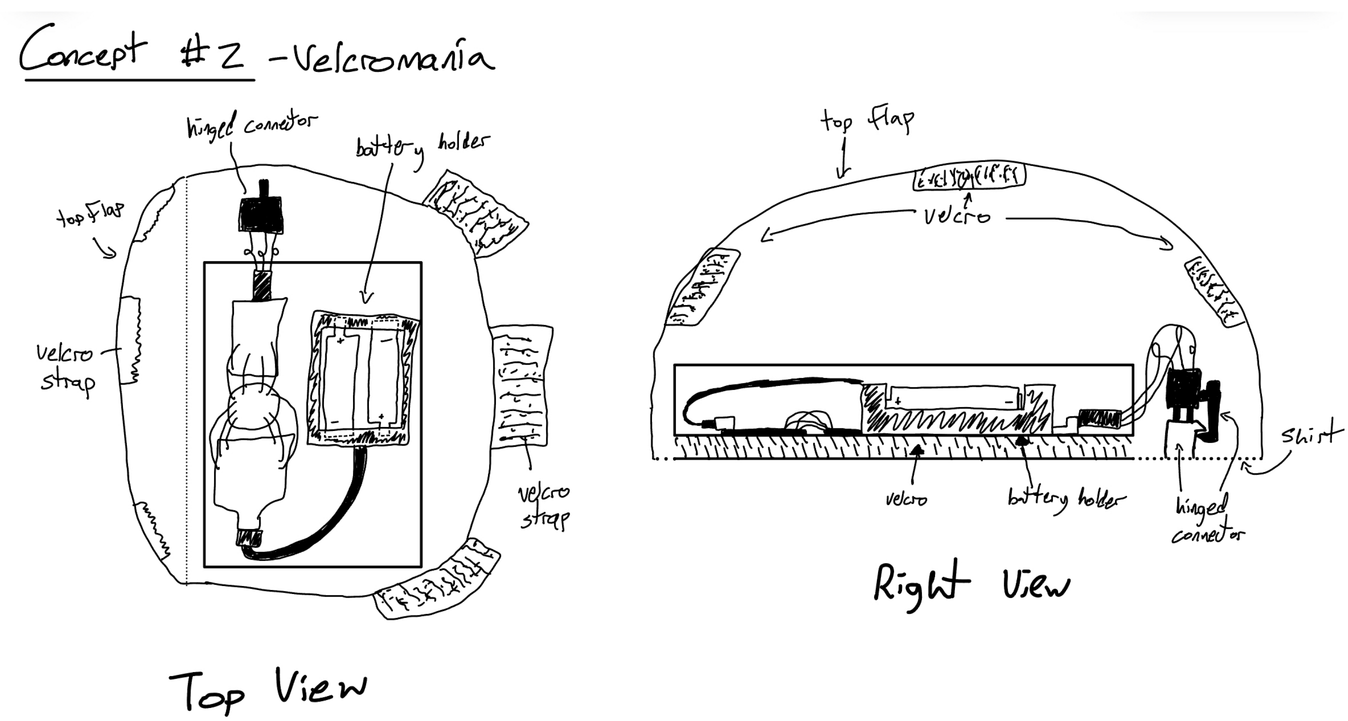


Figure 12: Sketches of the Velcromania concept

Description: This design consists of many velcro connections that keep the electronics and battery box in a fixed position when all the connections are together. The velcro also allows for the electronics to be easily removed when the shirt needs to be laundered. The hinged connector is likely the most ideal electrical connector available as it allows for multiple wires to be used in one connection, and it will not become disconnected until the user pressed down on the hinge. The electronics box is a square shape to make it more compact and comfortable on the shirt. This design will likely not be sufficient for a waterproof design as the velcro will not be able to seal the electronics from outside effects, but the priority for this function can be assessed at a later time.

3.4.3 Concept #3: Plug

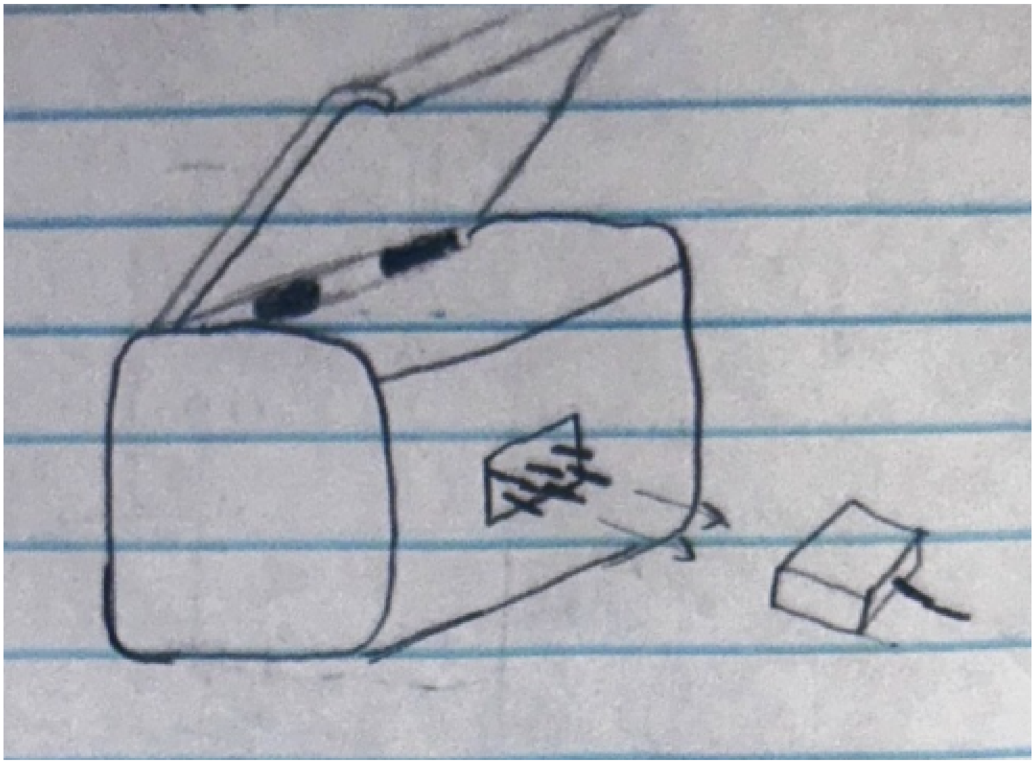


Figure 13: Sketch of Plug housing design

Description: This design features a single-piece door, opened via a hinge on the lengthwise edge of the enclosure, allowing for the most user-friendly and intuitive application. The enclosure would be 3D-printed for ease of manufacturing and low production costs. Additionally, there are no hard corners. All edges are rounded to increase comfort for the wearer and prevent stress concentration points that may damage the enclosure or the batteries during a sudden impact. Electrical connections are achieved using a plug system, where individual pins are tied to the conductive thread of the smart shirt.

3.4.4 Concept #4: Simple Kinda Man

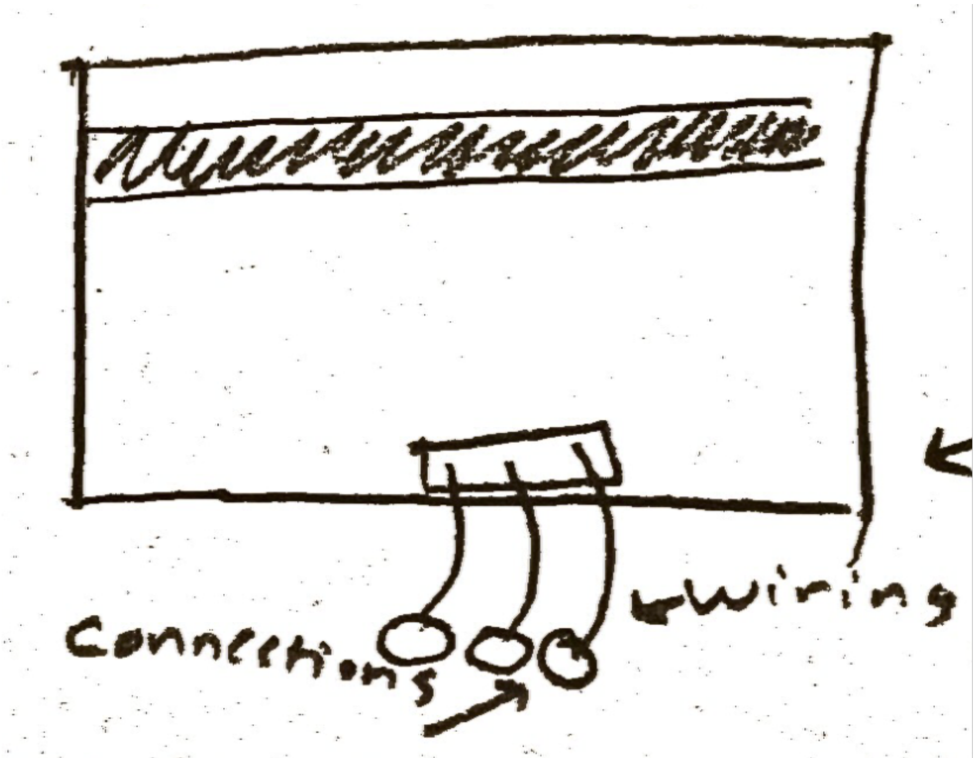


Figure 14: Sketch of SKM housing design

Description: This design is arguably the simplest of the conceptual designs. The enclosure features a standard rectangular box, with a slot cut out to allow the wires to reach the circuit board. This design utilizes a sliding-lid mechanism as opposed to a hinged door. Similar to the previous design, 3D printing will be used for ease of production and to reduce manufacturing costs. Electrical connections will continue to use snaps, that are easy to connect and disconnect and are highly user-friendly.

4 Concept Selection

4.1 Selection Criteria

The Analytic Hierarchy Process below was used to help us determine the most important criteria the best design should have to fix the current issues in the smart shirt. From this chart, it was determined that creating a battery housing that keeps the electrical connections in place was the most important problem the box needs to fix.

	Lightweight	Easy to remove	Keeps electronics safe	Box stays in place	Connections stay in place		Row Total	Weight Value	Weight (%)
Lighweight	1.00	3.00	0.33	0.33	0.20		4.87	0.10	9.79
Easy to remove	0.33	1.00	0.20	0.14	0.14		1.82	0.04	3.66
Keeps electronics safe	3.00	5.00	1.00	0.33	0.33		9.67	0.19	19.46
Box stays in place	3.00	7.00	3.00	1.00	0.33		14.33	0.29	28.85
Connections stay in place	5.00	7.00	3.00	3.00	1.00		19.00	0.38	38.24
						Column Total:	**49.69**	**1.00**	**100.00**

Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Using the criteria used in the Analytic Hierarchy Process, the following Weighted Scoring Matrix was created. After judging each concept's ability to handle each criterion, Concept 2 was selected as it had the most robust system for keeping the electronics safe, keeping the box in place, ensuring that the electrical connections maintain their connection to the shirt, and keeping the electronics safe from outside effects like moisture.

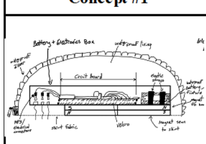
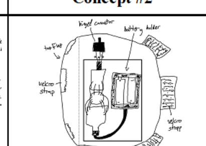
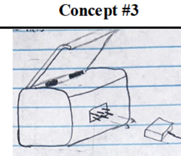
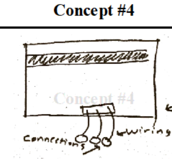
Alternative Design Concepts		**Concept #1**		**Concept #2**		**Concept #3**		**Concept #4**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Lighweight	20.00	2	0.40	3	0.60	3	0.60	3	0.60
Easy to remove	15.00	3	0.45	2	0.30	3	0.45	3	0.45
Keeps electronics safe	20.00	5	1.00	4	0.80	4	0.80	4	0.80
Stays in place	25.00	3	0.75	5	1.25	2	0.50	2	0.50
Connections stay in place	20.00	4	0.80	5	1.00	3	0.60	3	0.60
	Total score	**3.400**		**3.950**		**2.950**		**2.950**	
	Rank	**2**		**1**		**3**		**3**	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

It was determined that Concept 2 was the best design for these weighted criteria as it seemed to win in almost all the categories. For the lightweight category, all the designs were similar in weight. For ease of removal and attachment, it was determined that a magnetic connection would be easiest, but it would likely not be as secure and possibly cause electrical interference. Therefore, Velcro was determined to be the best for removing and attaching the electrical box because it will be both secure and easy to remove when necessary. The box was proposed to be waterproof, potentially with a gasket or with waterproof fabric, to keep the electronics safe. Concept 2 also had the best electrical connection as it will remain in place once it is snapped into place. The connector has a lever that needs to be pushed to remove it from the shirt, so it will be unlikely that the wires disconnect from the shirt unintentionally. It will also make it easy for the user to connect the electrical wires as it has just one connection with multiple wire interfaces as opposed to the three on the current prototype. A more detailed drawing of Concept 2 is shown in Figure 12.

4.4 Engineering Models/Relationships

Engineering Model 1 - Static Failure: It is essential to ensure that the battery box does not become damaged if a reasonable outside force is applied to it because the electronics or the person wearing the smart shirt could be harmed. Thus, it is essential to build the box out of a material that will not fail from the forces applied to the box. To calculate the points of failure for the box, the stress tensor can be constructed. The stresses are calculated by measuring the force and area at the points shown in Figure 17 below. From this matrix, the principal stresses can be calculated to find the points of failure. Once these points of failure are known, a material can be chosen that will withstand these failures or the box can be reinforced with more material at those points.

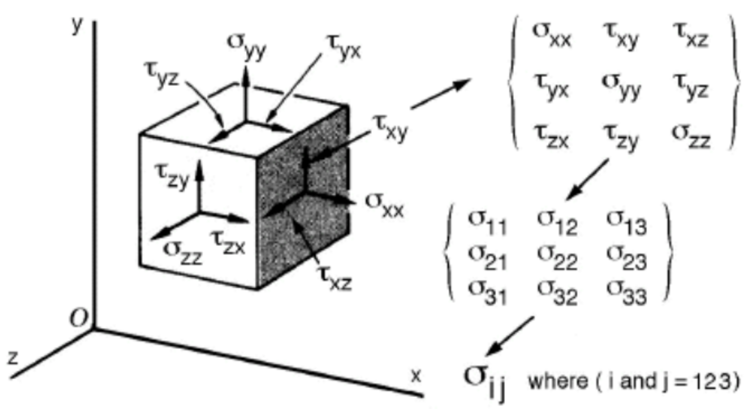


Figure 17: Engineering Model 1 - Static failure and the stress tensor matrix (Source)

Engineering Model 2 - Tolerances: When manufacturing any engineering concept, tolerances are one of the most important aspects that every engineer must consider when designing. For the WUSTL Smart Shirt electronic housing, tolerances will be important to ensure that all electronics in the box stay in place and that the connections used to open and close the housing will allow for movement without everything being too loose to too tight. Figure 18 shows some basic terminology used when specifying tolerances in an engineering drawing.

As tolerances are increased, the electronics enclosed are more free to move. For optimal security, the enclosure should closely follow the contour of the battery and its associated components. Low clearances result in greater frictional forces, securing the power bank to its enclosure. This helps to lower shock due to sudden impacts as well as reducing noise as the wearer moves. Both of these are fundamental to the purpose of this design.

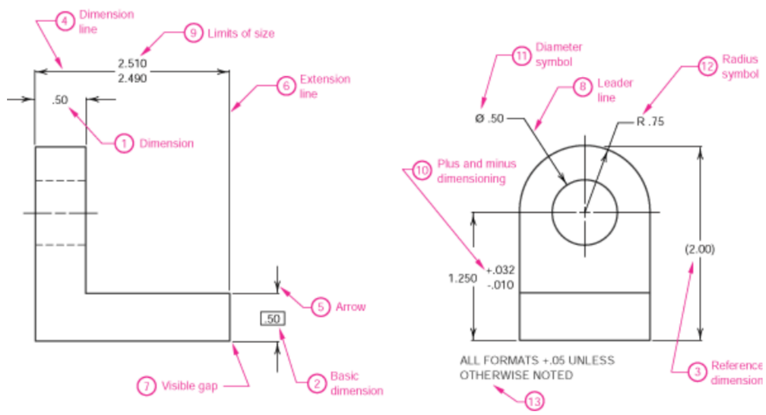


Figure 18: Engineering Model 2 - Basic terms used for specifying tolerances (Source)

Engineering Model 3 - Gaskets: If a design is chosen that will not be removable from the shirt, a gasket would be a great way to waterproof the design for the electronics housed in the box. The important things to note about a gasket are that uniform pressure is required for a good seal, as well as a compressing force to cause the pressure. Figure 19 shows what a gasket could look like if a rounded corner box design is used. An effective gasket would likely follow the perimeter of the hole being waterproofed.

As mentioned previously, a compressing force causing uniform pressure on the gasket is ideal, so a design with a latch, locking mechanism, or snap-on door would be ideal for a gasket design.

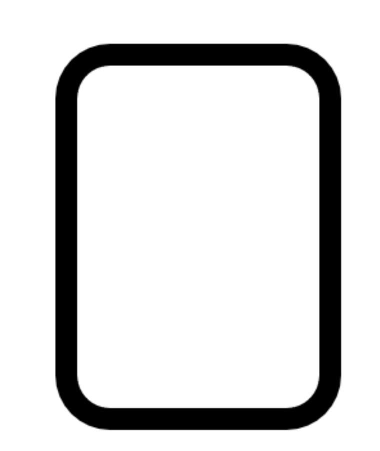


Figure 19: Engineering Model 3 - Potential gasket shape for door with rounded corners. (Source)

5 Concept Embodiment

5.1 Initial Embodiment

The initial embodiment is a 3-D printed, flat case, with internal foam cushioning for the electronics and a more reliable connection replacing the old, noisy snaps.

5.1.1 CAD Embodiment Drawings

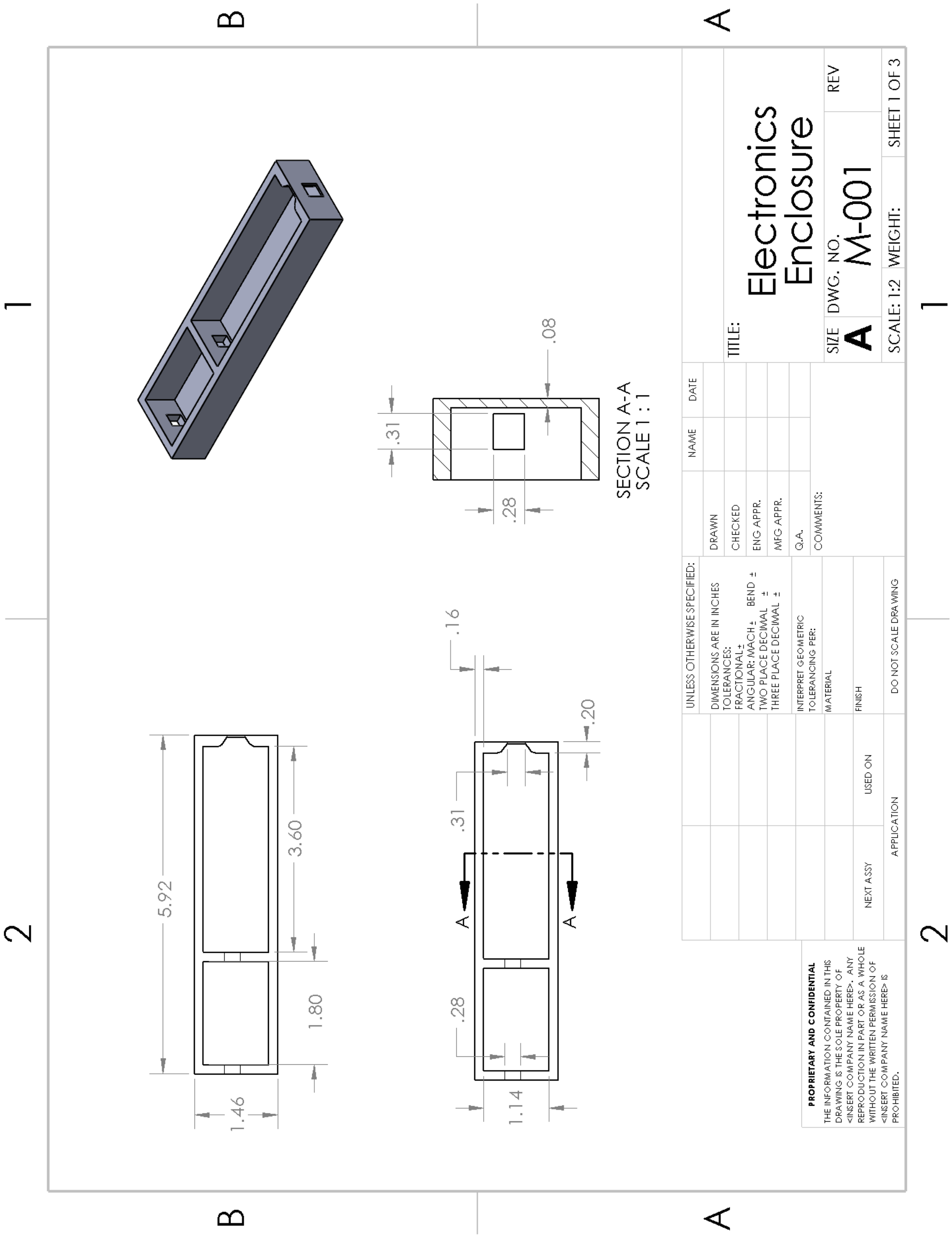


Figure 20: Electronics enclosure with overall dimensions

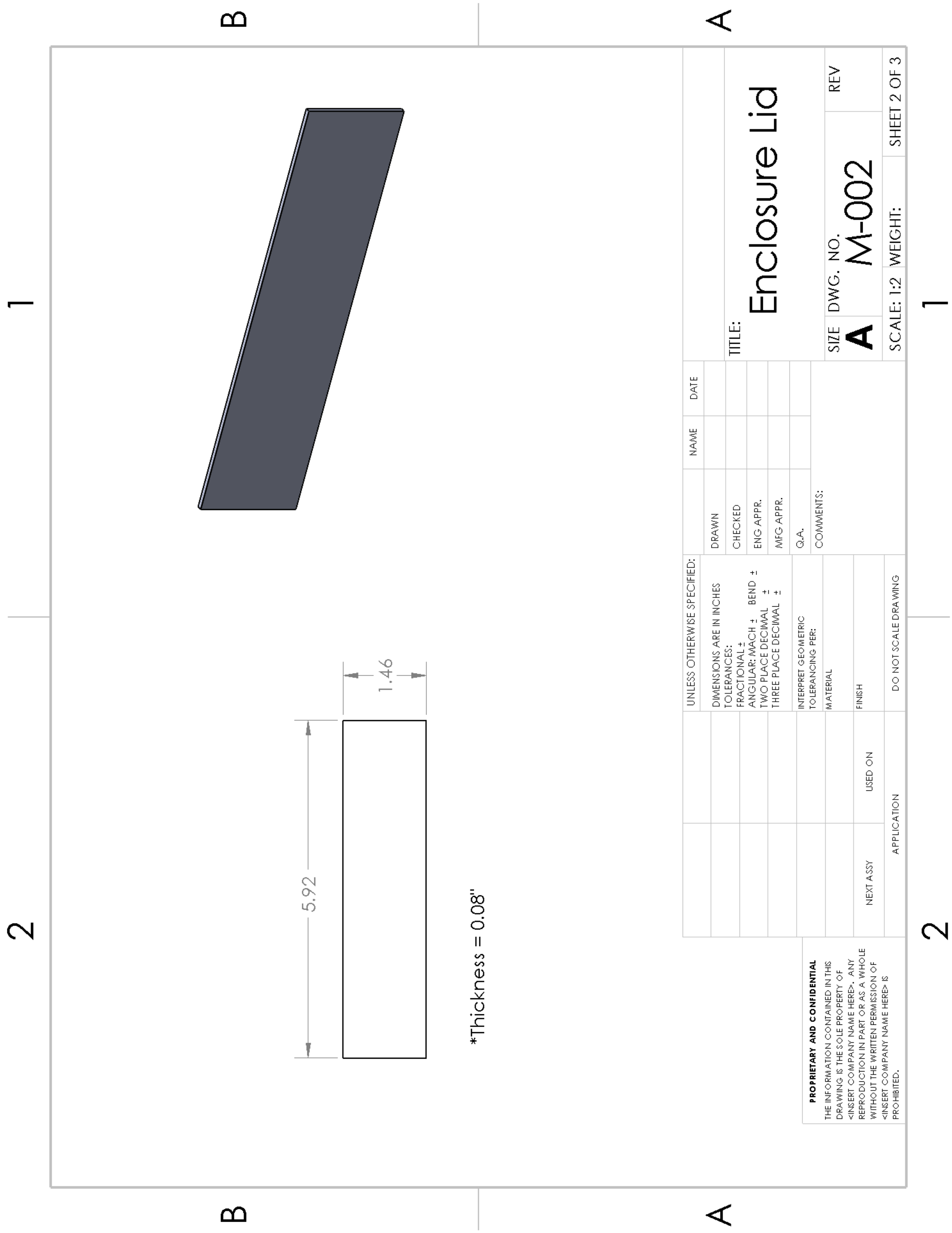


Figure 21: Enclosure lid with overall dimensions

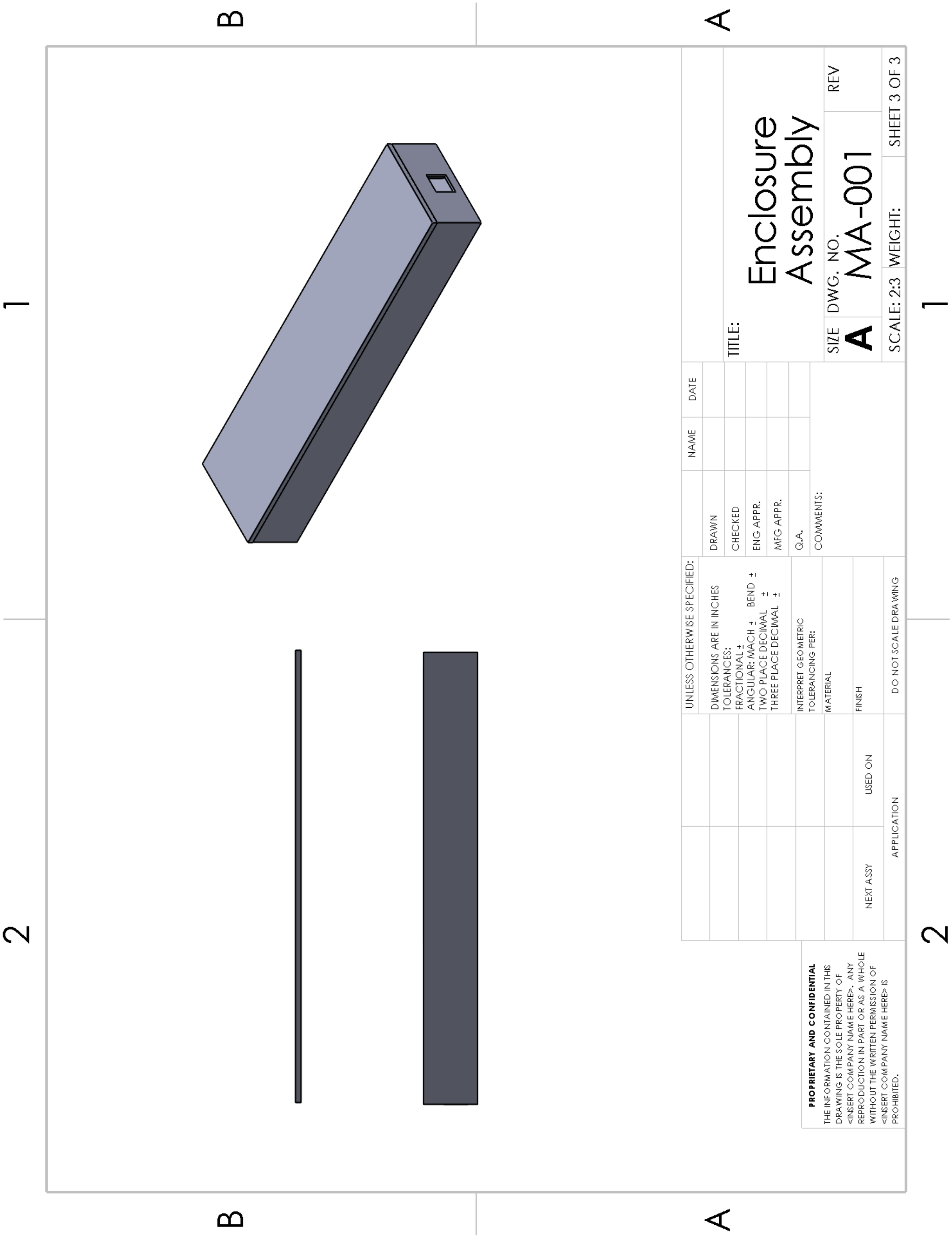


Figure 22: Exploded and assembled view of the electronics housing

5.1.2 Prototype Performance Goals

Three performance goals were selected to address key concerns in the final design: water resistance, reliable connectivity to conductive thread, and electronic protection.

To assess water resistance, the case was sealed with gasket-maker and submerged twice for over 30 seconds, simulating machine washing conditions. Both tests were successful, with no water penetrating the case.

A connection that was more reliable and less noisy than the snaps was found online that met all of the connections needs. The connection has a hinge snap on the top that keeps the connections secure whilst being able to removed it easily when necessary. To make the connection compatible with the shirt, small holes were drilled into the gold-plated prongs of the connections. To simulate the conductive thread in the smart shirt, fishing line was threaded through the holes. Since the fishing line fit through, the conductive thread should not have any problems providing power to the connection.

To protect the inner electronics, the case and foam were sealed around a potato chip, a material that is far less durable than the actual electronics. The case was dropped from chest height and reopened to reveal a completely intact chip, indicating that the electronics should survive as well.

5.2 Proofs-of-Concept

The original Proofs-of-Concept are very different from the current design. The current prototype completely seals the electronics inside to make it waterproof. This makes it difficult to access the electronics, however. It has proven to be challenging to make the box waterproof while having a hinged door design, so it will be important to evaluate how important it is for the case to be waterproof versus being able to access the electronics. The current prototypes were adopted from former prototypes made of a special material called Ninjaflex that provided support to the electronics in the shirt while maintaining flexibility. This material will be considered for future prototypes as it is also waterproof and lightweight.

5.3 Design Changes

The current design has maintained the same connection type as the original concept selection in Section 4 with some slight modifications. The current connection has three ports oriented horizontally for the electronic wiring of the shirt. The initial connector had 4 ports stacked on top of each other that made the connection bulky, while the current connector has a much lower profile. The metal prongs of the connector housing posed a challenge for connecting the conductive threads to the new connectors. However, since the prongs were thicker than the conductive threading, it was possible to drill the small holes in the prongs that would allow the conductive thread to easily attach to the new connections reliable. The current length of the design was also extended to allow for the electronics to be oriented in an optimal position. The current design was also adapted to have a fixed lid sealed with gasket maker than having a removable lid. A sealed case prevents outside effects like water damaging the electronics. Since the wiring won't be needed to be accessed once it has all been done correctly, this design works well since there are less moving parts. Also, the batteries are the only part that need to be removed occasionally for charging, but these will be separate from the electronics housing. The sealed design could be challenging if there are issues with the wiring once the case has been installed, which might need to be accounted for later.

6 Design Refinement

6.1 Model-Based Design Decisions

Model 1 - Tolerances: The dimensions of the electronics box were very important to get right because the ports needed to connect to the battery and smart shirt had to be exact, otherwise these connections to the outside could not be made. It was also important to make the inside of the box small enough so that the electronics would not move around, but large enough so that they would be effortless to put in place. In one of the final designs, the outline of the electronics was mapped precisely so that the electronics could be placed in the correct orientation easily. This was challenging as the decided tolerance range was -0.5 mm to +1.0 mm. This range was chosen because it was more important to make the molded shapes big enough to fit the individual pieces but more important to make sure the molds were not too small so that the pieces wouldn't fit. The pieces of the electronics housing were also completely 3D printed, so it was necessary to account for any mistakes in dimensions with a larger tolerance window.

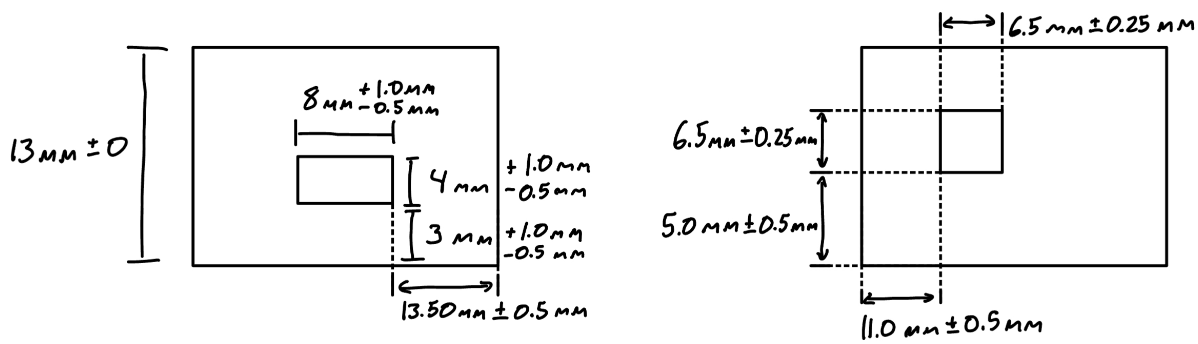


Figure 23: Sketch of Basic Tolerances of the Electronics Housing

Model 2 - Gasket: To make the electronics safe from outside moisture and make the box fully waterproof, a gasket was designed to be placed between to the lid and the main housing. After a couple of designs were made, it was determined that a functioning gasket could be created by 3D Printing the main housing using Ninjaflex, a flexible type of 3D Printed material, and 3D Printing the lid using PLA material. The dimensions were made such that there was a 0.1mm interference fit, allowing for the lid and the main body to be extremely tight together and waterproof. The dimensions are shown below in Figure 24 below.

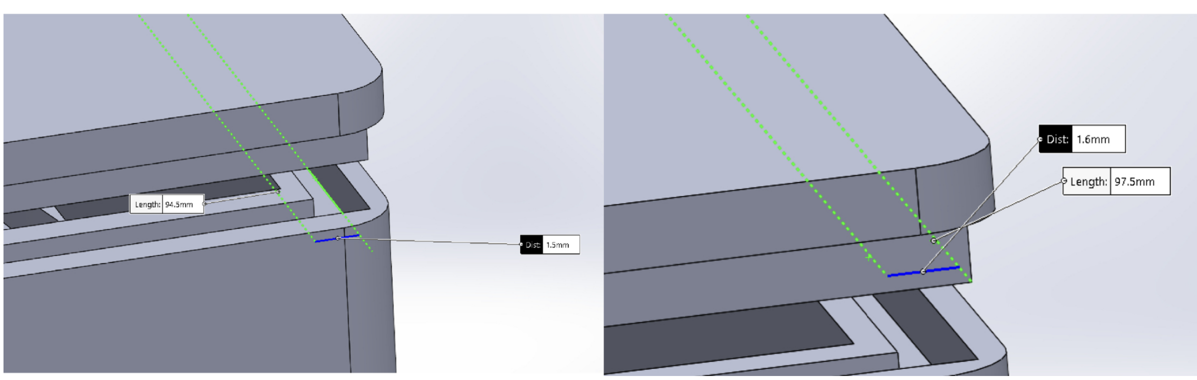


Figure 24: Interference Fit Dimensions of the Electronics Housing

6.2 Design for Safety

For all design projects, it is necessary to analyze all possible conditions and risk factors associated with the design. In this section, a set of five potential risks are discussed, along with rationale, likelihood, and suggested mitigating steps. These risks are then weighed in a "heat map" shown in Figure 25.

6.2.1 Risk #1: Battery Puncture

Description: The battery is ruptured due to shock or fracturing of the enclosure. This may be due to heavy use or sudden shocks such as dropping.

Severity: Catastrophic. Ruptures of lithium-ion batteries release tremendous amounts of heat as well as toxic fumes over a short period. Physical risks include severe skin and lung damage.

Probability: Unlikely. Under routine use and normal environmental conditions, it is not expected that the batteries will be damaged in this fashion. It would require significant heat or a sudden, concentrated impact to provide such conditions.

Mitigating Steps: Remove sharp points or edges internally. Allow for even distribution of stresses in the event of an impact.

6.2.2 Risk #2: Damage to Housing

Description: The housing breaks due to wear or shock. This also may occur in the event the electronics enclosure is dropped.

Severity: Critical. Similar to the above, damage to the housing risks damaging the batteries. In addition, a fractured enclosure poses the risk of cuts to the shirt or the wearer's skin.

Probability: Unlikely. It is not expected that the enclosure experiences such a force to break the material in any case other than being dropped.

Mitigating Steps: Provide sufficient material to withstand expected shocks and stresses. Ensure adequate thickness to withstand a drop of several feet in height.

6.2.3 Risk #3: Wear and Tear

Description: Instances of electrical or structural failure due to heavy use. Repetitions of wearing and removing the shirt, as well as removing the enclosure from the shirt due to washing may cause wear on the electrical connections over time.

Severity: Marginal. There are no serious health or safety risks due to failing connections. However, a reduction in the connections' quality will diminish the quality of the data acquired over time, harming the device's reliability.

Probability: Seldom. Electrical connections are exposed relative to the circuit board and will always be affected by any motion that occurs.

Mitigating Steps: Provide stronger and more reliable electrical connections. Ensure connections do not separate under greater-than-normal manipulation.

6.2.4 Risk #4: Sweat Damage

Description: Sweat enters the enclosure causing shorts, poor connections, and damage. There is a higher risk if the wearer sweats often or sweats heavier at night when the device is in use.

Severity: Critical. Though no health risks are expected any damage to the electrical connections will diminish the quality of the data collected. This would negate the functionality of the device.

Probability: Unlikely. A significant portion, if not, nearly all moisture released from the wearer should be absorbed by the fabric in the shirt, and it is unlikely there will be enough to penetrate the enclosure.

Mitigating Steps: Ensure a sufficiently tight seal to prevent any water access during normal use. The enclosure should be able to resist water when fully submerged to a depth of several inches.

6.2.5 Risk #5: Overheating of Battery

Description: Overheating of battery due to environment or overuse. Environment may include the room the user is present in and/or the body temperature of the user. Overuse may include leaving the device on for longer than the intended period for data acquisition.

Severity: Critical. Similar to the previous risks, the chances of battery rupture are significantly increased.

Probability: Unlikely. Typical conditioned spaces will not provide sufficient heat beyond the rated temperatures of the batteries. Additionally, the batteries shall not directly contact the skin, reducing the heat transfer between the two media.

Mitigating Steps: Provide sufficient ventilation for battery pack. Ensure batteries are elevated away from the skin.

6.2.6 Analysis of Risk Factors

Severity of risk	Category	Probability that something will go wrong: **Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
	Catastrophic					Battery Puncture
	Critical					Damage to Housing Overheating of Battery
	Marginal				Wear and Tear	Sweat Damage
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 25: Heat map of potential risk factors

The above figure displays a visual representation of the potential failures of the enclosure design. Important considerations include the severity of the risks and the frequency in which they might occur. In this model, it is concluded that the risks closest to the bottom-right corner require the least priority and those closest to the top-left require the most attention. As it is related to several previously discussed failures, a battery puncture would be the most hazardous due to its extreme severity. The impact of toxic fumes and high heat significantly outweighs any other outcomes in the event of failure. Next is the battery overheating. While the same outcomes as above would occur in such an event, it is less likely it will occur due to environmental conditions. Damage to the housing, while unlikely, may cause harm to the user if the enclosure fragments or cracks due to an impact. The least significant were determined to be sweat damage and wear and tear. It is highly unlikely that the user would produce enough sweat over the course of one night to penetrate the seal of the lid, provided that the lid is elevated off the skin. Additionally, normal use would not ruin the connections in any short period. Any resulting damage would affect the connections to the electrodes, which provides no physical hazard.

6.3 Design for Manufacturing

There are a total of 12 parts in our design: the main electronics housing body, the housing lid, the electronic board, two outlet wire connections, the electrical connector to the shirt and its three metal ports, the battery housing, and two batteries. There are no threaded fasteners. The theoretically necessary parts are the main housing, the circuit board, the battery, and the shirt connections. The main housing is necessary because it contains all the electronics and important aspects of the smart shirt. The lid is not necessarily important because the lid and the housing can likely be combined into one piece that functions the same. The circuit board is necessary because it relates all the data coming from the shirt into data that can be analyzed. It will could be changed in shape or size in the future if such accommodations are necessary. The battery connection is important because they supply power to the whole shirt and the circuit board, so this component is essential to every aspect of the shirt. The shirt connections are necessary because they supply power to the shirt and provide feedback that the circuit board can interpret. Without these connectors, the smart shirt would not function at all. There could theoretically be a Bluetooth connection that could be made between the shirt and the circuit board, but there will still need to be connection wire to the shirt from the battery.

A was that the total number of components could be minimized would be to combine the battery housing with the lid or attach it on the side of the circuit board housing. By attaching the battery housing to the lid, it makes all of the electronics significantly thinner, but then the electronics are taller and could be uncomfortable for the user. Conversely, if the battery is placed on the side of the circuit housing, that could also be uncomfortable. In our final design we believe that attaching the battery to the circuit housing lid will be the best option, and have some ideas on how to minimize the overall height to make the electronics as comfortable as possible. A possible design is shown below in Figure 26.

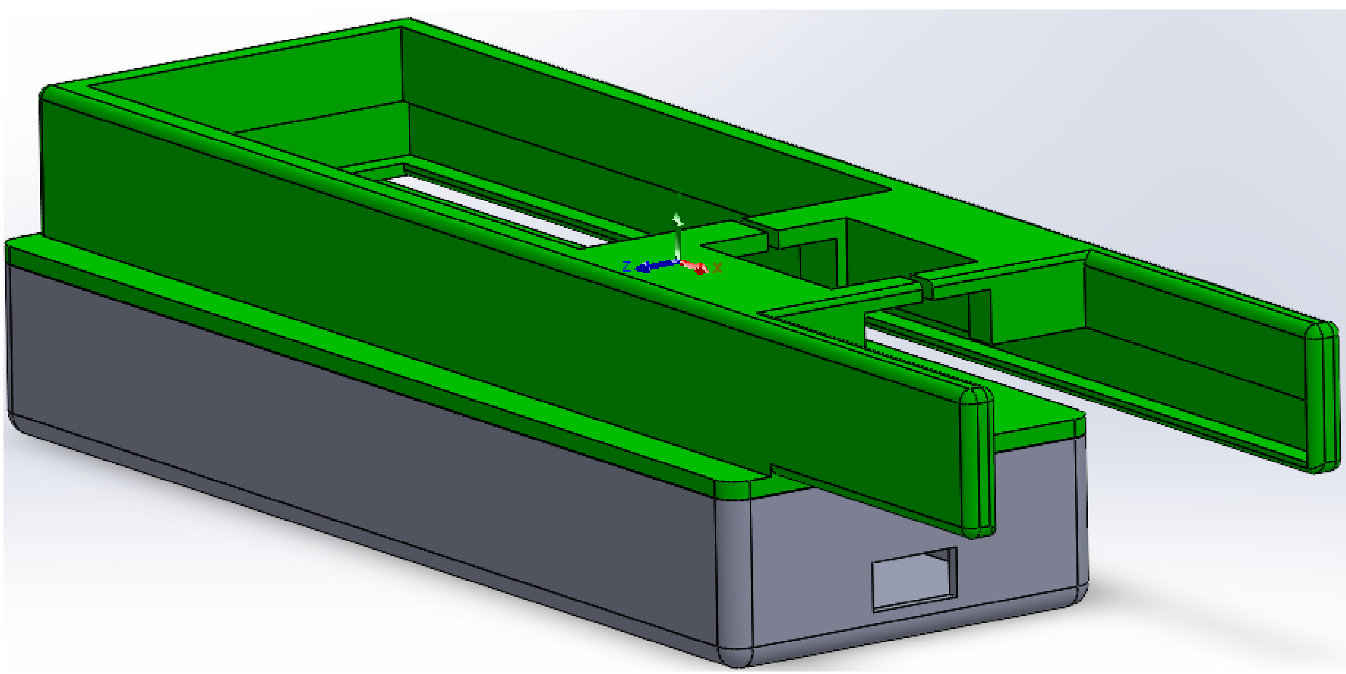


Figure 26: Possible Improved Design with the Battery Housing and the Circuit Board Housing Lid Combined

6.4 Design for Usability

It is essential to consider how a design will be used by the customer, and how easy operation is for the user. Below is a basic analysis of the difficulties that may arise in this design due to common impairments. These include visual, hearing, physical, and control impairments, which may be common among many people who may utilize this product.

Vision impairment may make this device more difficult to use if the housing has small features. Because there are several locations for electrical connections, it would be difficult to decipher which wire must go to what terminal. In addition, it might also be difficult to be able to separate the battery from the housing if it became necessary to do so.

Hearing impairment should have a negligible effect on this device. In the extremely rare possibility that the battery is ruptured, there will be a sound of gasses forming and escaping rapidly. This reaction would be accompanied by extreme heat and possible flaming.

With a physical impairment, such as arthritis, muscle weakness, or limb immobilization, this device may be more difficult to use with smaller features. For our device, the electrical connections are very small and move with the fabric of the shirt. With an unsteady hand, trying to establish good connections between the electrodes and the battery housing may be a significant inconvenience.

Control impairments would likely lead to the above impairments and be met with similar challenges. Besides inconvenient difficulties, a significant risk is associated with a battery rupture, which could be caused by the housing or user error.

6.5 Design Considerations

Table 3: Factors considered for design solution

Design Factor	**Applicable**	**Not Applicable**
Public Health		X
Safety	X	
Welfare	X	
Global		X
Cultural		X
Societal		X
Environmental		X
Economic		X

Table 4: Contexts considered for ethical judgments

Situation	**Applicable**	**Not Applicable**
Global context		X
Economic context		X
Environmental context		X
Societal context		X

7 Final Prototype

7.1 Overview

For our final design, we decided that the base of the electronics holder would be made out of Ninjaflex and that the lid would be made out of PLA as well as hold the batteries. This was the best combination as it allowed for the electronics to be safe from any impacts or drops and reduce the number of components in the design.

Figure 27 below shows what the assembled electronics box and lid look like from the top of the design.

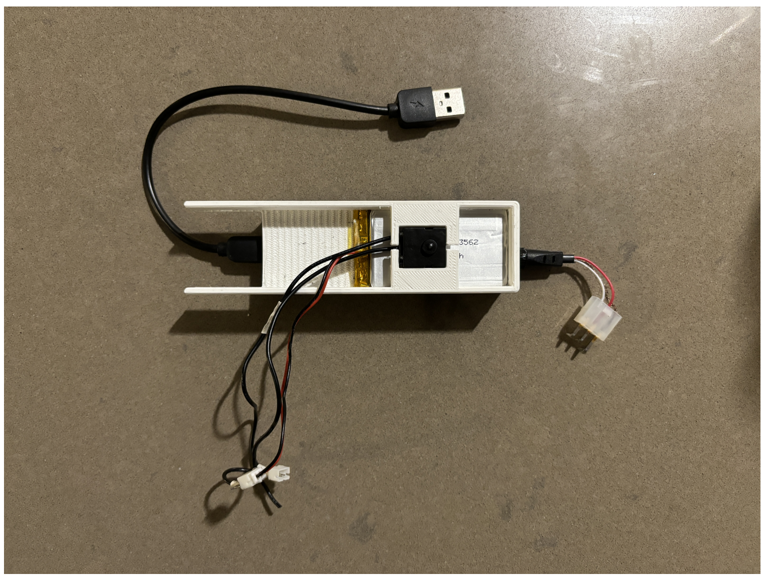


Figure 27: Top View of the Final Design.

The USB chord exiting the box from the left is designed to connect the battery to the circuit board inside the box while the electrical connector on the right is to be attached to the shirt to obtain the biometric data from the wearer of the shirt.

Figure 28 shows the two main pieces of the final design.

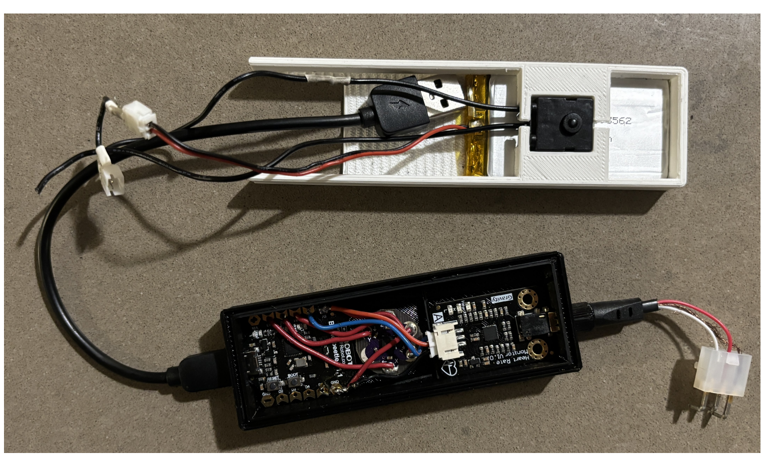


Figure 28: Final Design Components.

The electronics lid is made out of white PLA material and holds the two batteries needed to power the electronics for the smart shirt. The main body was made of black, flexible Ninjaflex TPU material. This material was chosen because it will be very comfortable for the wearer of the shirt as it does not have an sharp edges and is flexible to account for changes in position when wearing the shirt. It was also made to match the exact dimensions of the electronics inside, so they will not move around when wearing the shirt. The Ninjaflex material also creates a seal with the hard PLA material so that no moisture or water can make it to the electronics inside.

Figure 29 shows a closer view of the final produce.

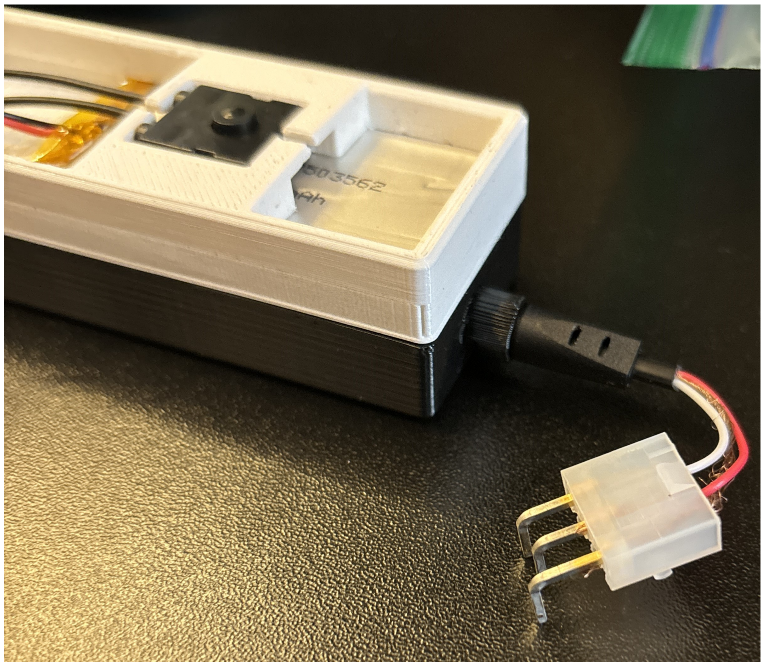


Figure 29: Close-up view of the Final Product.

This image shows how well the PLA and Ninjaflex seal together. The Ninjaflex body was also designed to seal the audio jack port from outside moisture to make the electronics as waterproof as possible.

Figure 30 shows a close-up view of the final Ninjaflex main body.

Figure 30: Final Ninjaflex Design of the Main Body

The holes on the top of the body were designed so that the top lid would have an interference fit and snap into place on the Ninjaflex body to seal the electronics from outside moisture. On the inside of the body, the model was designed so that the electronics would fit perfectly into the cutout slots to prevent any movement. Finally, the circular extrusion on the outside of the housing was designed to fit the audio jack port perfectly and seal the port from any outside moisture.

Figure 31 shows a closer view of the finalized battery lid.

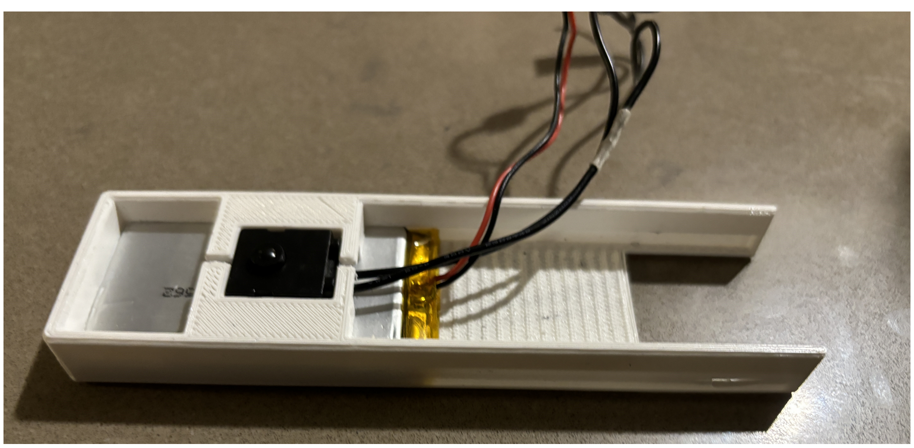


Figure 31: Finalized Battery Lid

The final lid design incorporated the batteries of the system to reduce the overall number of parts in the design and move the batteries further from the chest of the shirt wearer. This design also makes it easier for the shirt wearer to turn the electronics on and off with the black switch located on top of the batteries.

The finalized shirt connection is shown in Figure 32 below.

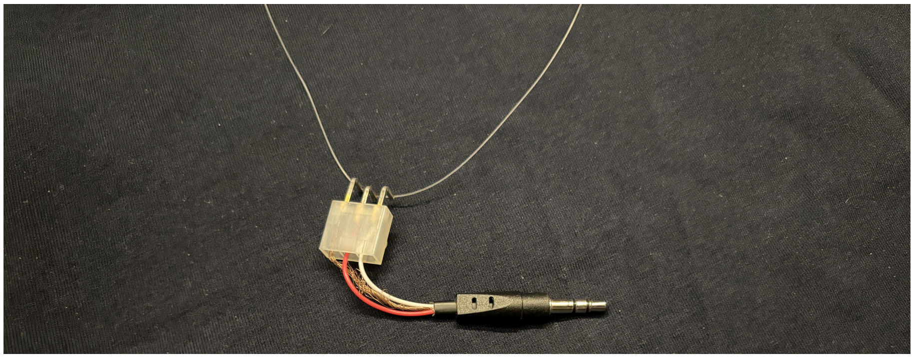


Figure 32: Final Shirt Connection.

This connection was chosen for the final design because it will provide a reliable connection to the electronics without interruption. The plastic housing will be sewn onto the shirt and the audio jack port will connect to the electronics in the Ninjaflex housing. The three metal prongs will be attached to the conductive threading inside the shirt that goes to the two electrodes and the ground to collect biometric data. The fishing line in the picture was used to simulate the size of the conductive threading.

The final design was able to reach all the prototype goals. It was found to be very durable as it was able to sustain multiple drops from chest height while keeping the electronics intact. The final design was also able to keep water and moisture from entering through the lid. The audio jack was also able to create an effective plug to keep moisture from entering in through the side hole. Finally, the connection to the shirt was able to provide a constant circuit between the battery and conductive threading of the shirt.