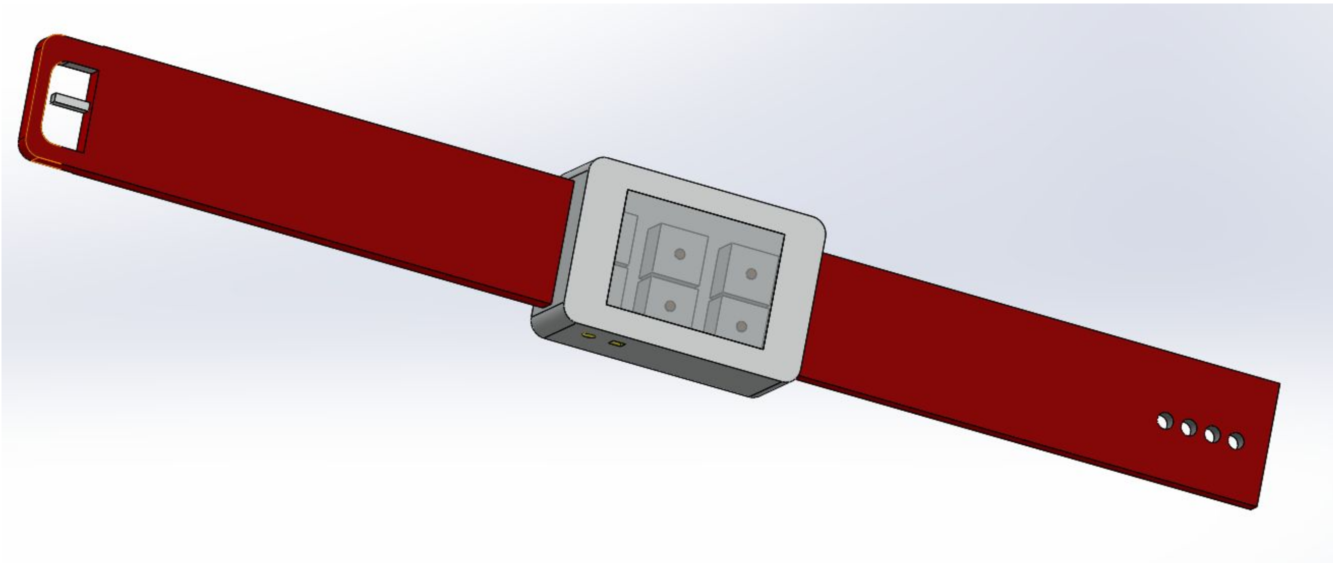
Bandit

"Take What You Need"



A Modular Sensor Package for Triathletes

MSE 4410 Senior Design I
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Executive Summary:

This paper is a detailed report of what our group has learned and achieved this semester in Capstone Design I. There were 6 main objectives for this class, as follows:

1. Learn the concepts of engineering design including integrated product/process development, quality function deployment (QFD) and DFX (design for manufacturability, quality, affordability, etc.)
2. Apply analysis and synthesis skills by utilizing knowledge and fundamentals learned from other courses in the curriculum to work on open-ended design projects.
3. Gain an appreciation for team-oriented activities through work on design teams exploring the various facets of product/process design and development in materials – polymers, fibers, ceramics, metals, and textiles.
4. Contribute effectively to multidisciplinary design teams in the real world.
5. Develop oral and written communication skills for technical information.
6. Learn the importance of engineering ethics in the practice of the engineering profession.

Starting from brainstorming project ideas for the semester, our group members have stepped through the entire process of engineering design. We have developed a mission statement, identified consumer needs, established product specifications, generated concepts, selected and tested concepts, considered product architecture and industrial design, and finally, made sure that our process considered environmental impact as well as manufacturability. As engineering design is an iterative process, we have critically analyzed our progress and status after every step, making sure to reflect on our gained experiences for future tasks. At many points along the continuum, we have taken steps back to slightly alter or even completely redo previous design choices in order to produce the most optimal product based on our best judgment. To this end, we have also created a minimum viable product for demonstration. The following is a walk-through of our process and accomplishments in chronological order.

I. Pre-Pivot Efforts

The following section details all of our group work up until our pivot into our final mission statement. Starting from knowing next to nothing about engineering design, we collectively made many decisions that we would later rescind as we learned more through reading the textbook and class lectures. An argument can be made that learning itself is an iterative process, and it is with the purpose of reflection that we begin our narration of the journey through the past semester.

A. Initial Ideas

The first assignment for the class was to come up with three project ideas that we would want to work on for the semester. With no data on user needs, these ideas were created based on assumed needs. The following is a summary of the ideas that each group member brought to the table:

Qi

- Speaker for dog commands for the mute
- Voice recognition for object searching via attached dongle
- Charging music players via foot motion

Tony

- Solution to increasing FDM parts' strength in the Z direction for 3D printing
- Fabric structures designed for ease of setup and takedown using shape memory alloys
- Thick water-holding fabric with surface finishes for specific applications; ability to hold more water than current products.

Hayley

- Portable energy harvester through body motion
- Replace ITO screens with graphene based crystals
- Transitional metal oxides for photodetectors which are more sensitive that current detectors and less dependent on temperature

Jessica

- Removable keyboard for laptops made out of light, sturdy, and modular components which can be used wirelessly
- Clothes material that won't wrinkle, especially for suits
- Self-charging batteries via alternative power sources

After we shared our ideas for the project, we assessed what would be the best idea given our background knowledge, skills, and interest. We concluded that approaching the project idea from this angle would directly relate to the quality of work that each member would contribute as well as team motivation for the project. The following is a list of the skills and knowledge that we had already:

> Secondary battery research, robotics sensors, hardware programming, web application development, front end web development, startup development process, thin films, optical detectors, magnetic materials, transitional metal oxides, materials characterization equipment at Georgia Tech (XRD/SEM)

Our ideas lent themselves well to tackling the project from a technology push perspective as most of them involved novel ideas rather than improvements on existing solutions. By the end of the first meeting we came to the conclusion that energy harvesting and energy storage would be ideal topics to explore. Our initial perceived need was that mountaineers and hikers who take extended trips need more long-term and reliable power sources for their electronic devices than what was currently available. Even though our mission statement would later pivot as we learned more from the class and peer feedback, it was this idea that we centered our first mission statement around.

B. Initial Mission Statement

Our initial mission statement was carefully constructed after considering the benefit the product would have for the customers, the goal for the product, primary and secondary markets, assumptions, constraints, and the stakeholders. It was structured to describe answer the questions posed by the interrogatives what, who, and why. Table 1 summarizes the key details of our goal.

Initial Mission Statement:

Our mission is to develop a wearable device which will address the energy needs of those participating in extend outdoor activities, especially when traditional sources of power are not available.

Table 1. Initial Mission Statement Details

Benefit	Small, lighter than current solution to energy needs, constant reliable energy, wearable
Goals	Profit, to make it a product that is a necessity instead of a luxury for mountaineers, durable, environmentally friendly
Specific Population	Mountaineers
Secondary Market	Cold-weather campers
Assumptions and Constraints	People will be willing to pay a premium for quality, need exists, current source of energy is not sufficient. Limited technology to provide this service, it should be unobtrusive, it should be comfortable to use.
Stakeholder	People already manufacturing outdoor recreation products, purchasers and users, manufacturing operations, service operations, distributors and resellers.

C. Identifying Customer Needs

After we had a clear direction of where our project was headed, we put together a consumer survey to either verify or disprove our perceived user needs. Since we were approaching the project from a technology push perspective, it was important for us to figure out what types of devices our consumers already used on their trips as well as what problems existed for these devices. In the case that our perceived user needs were not relevant, we provided unbiased questions which allowed for surveyees to indicate such.

1. Gathering Raw Data

We were curious about the duration of the outdoor activities, the types of electronics people used, what other functions were desired, temperature range for the activities, and how much people would be willing to pay for the gear. A customer survey was conducted over Google Forms and the following questions were asked:

1. What kind of outdoor activities do you do?
2. For each activity, how often do you participate in them?
3. For each activity, how much time do you spend per trip?
4. For each activity, what's the temperature range you've experienced?

5. For each activity, what type of electronics do you bring?
6. For each activity, how do you navigate (if applicable)?
7. How much gear do you take with you when doing these activities?
8. Please describe how you determine which equipment to buy
9. Rank from most important to least: cost, durability, environmental friendliness, ease-of-use, comfort
10. Suggestions/comments

We received a total of 41 responses from athletes who participated in 22 different kinds of sports. 76% of the people indicated that the only electronic device they needed was their cellular phone. The vast majority of the activities other than hiking and camping took less than 5 hours, and of the 15 who enjoyed hiking and camping, only 1 used an electronic device other than a phone. 13 out of 15 hikers/camper used paper maps for navigation.

2. Interviews and Consultations

Our group members met up with Outdoor Recreation at Georgia Tech (ORGT), which is an official SGA-chartered organization in charge of the outdoor recreation activities for those associated with Georgia Tech. One of the members showed us the types of equipment and sensor devices they use for outdoor trips lasting upwards of one week. We learned that electronic equipment was hardly needed for these activities - campers and hikers prefer more traditional ways of navigating their route, making use of paper maps. Devices used were mostly limited to location trackers which would emit an emergency beacon, and any electronic devices taken used alkaline batteries due to their low energy needs and requirement for long shelf-life. A lot of campers do bring their cell phones with them, but those that did never expressed a need for recharging while on their excursion.

We also interviewed a professor from the Korea Advanced Institute of Science and Technology (KAIST) who developed a wearable thermoelectric generator (TEG) that could generate energy between the difference of the body temperature and the atmosphere [1]. We interviewed this professor as we thought that this technology could potentially replace the heavier energy sources used in outdoor equipment and extend battery life. However, the professor informed us that amount of energy generated by the TEG is not even a tenth of the energy needed to power a smartwatch. The TEG was intended for use with devices which require less than 3 mW of power, which makes it serviceable only under very specific circumstances. A transcript of Dr. Cho's comments can be found in the appendix as Figure A1.

Lastly, we interviewed Dr. Hong of Daegu Gyeongbuk Institute of Science and Technology (DGIST) of Korea who is an expert on battery research for general knowledge about secondary batteries (lithium ion batteries). A full transcript can be found in Figure A2 in the appendix.

3. Interpreting raw data in terms of customer needs

The results from the survey indicated that the need for electronics during extended outdoor activities was severely overestimated as most athletes do not carry electronic devices for their activities. Among our primary market of mountaineers and similar enthusiasts, there was little to no need for a solution to a problem which could be solved with a new electronic device, neither was there an issue with the battery life for existing devices.

After interviewing the two professors regarding new types of power sourcing methods, we realized that it was out of our scope to develop a completely new battery or energy harvesting system as it would require years of research. Even if we wanted to utilize existing TEG technology, there was not a developed technology which could power enough energy for the vast majority of consumer devices. Upon these realizations and considering the time we had remaining, our best move was to pivot to something within the scope of the course that satisfied an existing user need.

D. Pivot into New Mission Statement

We realized that we needed to keep our skills relevant to the project, but didn't want to invent something from scratch. Developing a completely new power source was out of our scope for a one semester project, hence, we brought the project down to a more tangible scope where we would optimize the technology that already existed but integrate it with a novel approach. The existence of a current technology would also guarantee the existence of associated user needs, which meant we would not be in danger of investing time into finding dead ends. Table 2 summarizes our new mission statement.

Final Mission Statement:

We aim to develop a modular sensor package which will address the data collection needs of triathletes so that they can better train for their events.

Table 2. Final Mission Statement Details

Benefit	Lighter due to only using requisite sensors, cheaper, more comfortable, more features, more durable than current competition, no phone required during data collection
Goals	Design a customizable modular sensor platform that provides a seamless user experience while guaranteeing accurate data
Specific Population	Triathletes
Secondary Market	Runners, bikers, swimmers, and high speed sports
Assumptions and Constraints	People desire the ability to customize their activity tracker. There is a way to design both a smaller and more comfortable sensor package. Mobile app integration, skin-contact, crowded market- need strong benefits to win customers
Stakeholder	Purchasers and users, manufacturing operation, service operations, distributors and resellers

II. Concept Development

A. User Needs and ITYs

After creating the new mission statement, we conducted a secondary survey of just triathletes and those who run, bike, or swim. Surveyees were asked to rank in order of importance durability, ease of use, comfort, environment friendliness, and cost for a performance tracker. The results from this survey suggested that the ideal activity activity tracker would be comfortable, low-cost, and easy to use. From here, our task was to translate what was conveyed in the consumer survey into specific development goals by identifying user needs. Establishing user needs ensured our product design was focused on consumer demands, something we were unable to do with our first mission statement. Our survey indicated that consumers prefer a wide variety of sensors, which is why we focused on a modular design where the user could swap sensors based on their training needs. This feature would improve the usability of our device and provide a more versatile tracking band for users. Comfort would ideally be better than competitor products since weight would be reduced and by purchasing only the sensors needed separately from the band, costs could be minimized.

Following the process described in the textbook, we extrapolated the results into user needs and grouped them into supergroups labelled with ITYs. User needs were also generated from features of similar products in the market such as the Tempo trainer and Node+, among others by comparing weighted metrics. We then prioritized user needs for our own product by combining the results from analyzing survey results, our own inputs as design engineers, and data-driven prioritization matrices. Table A1 in the appendix allowed us to compare the relative importance of various ways to gauge activity tracker quality and relative performance of currently available bands to each other. The complete performance requirements and grouped ITYs from this exercise are illustrated in Figure A3.

Since our product would have direct contact with the consumer's skin, safety was initially chosen as our number one priority, though the ordering would change later. For the needs-metrics matrix, tests were chosen to demonstrate safety by measuring skin irritation and battery safety risks. Functionality also scored highly, so metrics were developed to quantify the ability of our product to swap in and swap out sensors based on the data the user wants to track. Other metrics were systematically generated in a similar manner by considering possible ways to quantify performance for needs we determined to be important and then looking up standardized testing methods. Some needs required subjective test methods whose details were left open-ended until creating the ideal and marginal values table. The Needs-Metrics matrix can be found in the appendix as Table A2.

Our team's ranking discussion and assignment of testing metrics was designed to provide a balanced objective and subjective approach to the product design process, one that would hold up to quantifiable results without stifling creativity and human perceptions of quality.

B. Ideal and Marginal Values

From needs-metrics, we needed to come up with a way to quantify each metric, even if that meant assigning a numerical value to subjective user perception tests. Every need was bounded by a marginal and ideal value. Doing so allowed us to make tradeoffs when designing the product. Though all values should strive to be ideal, that is not a realistic goal, and so settling somewhere between marginal and ideal would allow us to continue development instead of stagnate.

Accordingly, we decided marginal values based on current products because we knew that competitors were still doing well at those values. Most of the marginal values came from research on corresponding performance trackers in the market, including the Fitbit, amongst those mentioned previously. Ideal values are the best result our team could hope for; for example, the total mass of our product should be or be less than 100 g, but other products in the market are heavier, generally around 150g, a weight that still allows the products to sell well. We set ideal values based on discussion on what we thought were just within the realm of possibilities to achieve. Our mindset was that marginal values should be rigorously set to guarantee our product to perform on par with competitors, but ideal values should encourage us to test our limits of design.

The importance rating of each metric was derived from the importance rating of the corresponding user need and ITY, balanced with survey results and our own judgment; for instance, according to our customer survey, the precision of reported data is the most important with a rating of 5 as that would fall under functionality, but antibacterial properties were hardly mentioned in the survey even though safety was our own #1 ITY, netting a rating of 2. Table A3 shows the marginal values and ideal values of each metric.

C. Concept Selection

Concept selection began with consideration of our ideal and marginal values and an analysis of the Fitbit, the current market leader in fitness trackers. Having approached our product design from a technology push direction, we wanted to produce various modular band concepts. However, we also did not want to limit our vision to what we had in mind since the mission statement pivot, so we looked into other concept paradigms such as tattoo based sensors [2].

During the concept creation process, we split ourselves up so that each individual could specialize on one part from the entire sensor package design. From the mission statement, we knew there needed to be some sort of band, sensor, sensor housing with display, and energy source to realize our vision for the product. This modularity of our concept design can be found in the function diagram we generated as Figure A4. Concepts A through E were generated first by coming up with various solutions for each component and then forming combinations after group discussion. The tattoo-based concept F was collectively proposed. Material selections for each of the concepts such as plastic or metal for the band are more indicative of the form factor and behavior of the concept, and less of a material selection decision. A summary of the concepts put forward for consideration are listed below, and ideas for the individual components can be found in Figure A5.

A: Low-profile Li-ion battery, Nylon band, socket enclosure, USART/UART communication

B: Metal wristband paired with TEG/Li-ion battery, sliding metal bars for sensors, and NFC

C: Silicone-rubber, TEG/Li-ion battery, clip-on design, using Bluetooth

D: Plastic band, Li-ion battery, clip-on sensors, with USART/UART

E: Nylon band with Li-ion battery, metal bar connection mechanism, and USART/UART

F: Waterproof tattoo based sensors applied to skin before every activity

Reference Concept: Nike Fitbit Charge HR – Lithium polymer battery, non-latex elastomer band with built-in sensors

Using an initial concept selection table, we were able to choose which concepts to move forward with by comparing individual concept performance to the reference Fitbit in Table A4. Selection criteria were chosen based on our most important ITYs and discussion among the team about which aspects we perceived to be most important when comparing concepts amongst themselves. Once we identified promising concepts, we utilized the concept scoring matrix seen in Table A5. At this point in time, we had just finished our midterm presentation, we decided to change our ITY order of importance to better reflect our product use case based on Graham's and peer feedback.

User Needs:

1. Functionality
2. Wearability
3. Safety
4. Durability
5. Usability
6. Aesthetics
7. Affordability
8. Novelty

Weights for our selection criteria were determined after group discussion on anticipated user judgment when comparing our product to competitors. We referenced our reprioritized ITY list to fine-tune the weights if there were disagreements. Our final concept chosen was determined based on highest score on the concept scoring matrix seen in Table A5 in the appendix. With our selection of concept E, we moved on to system-level design, focusing on materials and manufacturing choices which would fall between marginal and ideal values. Though in our concepts we had already selected preliminary materials for various components, we were sure to revisit our selections with scrutiny once our physical form factor was finalized.

III. System-Level Design

With our concept decided, the actual design and material selection portion of product development became our main focus. Given the ambitious scope of our project, we determined it would be best to continue with our depth-first approach of assigning one component to each person. As each person had already gained expertise in his or her one area of the product during concept selection, we also believed this approach to be the most efficient.

The following section describes in detail which design priorities were made in relation to perceived user needs and the new set of ITYs selected for each component. Special attention was given to the trade-offs required when decisions were mutually dependent. In this section, marginal and ideal values from before were referenced when considering the details that would go into each part.

A. Band (Jessica)

According to needs analysis, we concluded that the band material should be small in size and lightweight. The band would have a sensor housing that would be added onto it, adding to the weight. It would be important that the band's weight be minimized while not compromising on strength. The size should be small as we did not want the product to hinder the motion and movement of the consumer, but not so small as to be uncomfortable due to high constrictive pressure. It was important to design the product to be waterproof since triathletes and swimmers are often fully immersed. Upon leaving the water, we concluded that it should also desiccate quickly; preferably in seconds, but at the most less than a few minutes. This type of performance is generally found in impermeable materials. Since this product would be used in direct contact with skin, the material of the band should be carefully selected so that it does not cause harm to the skin. We had to search for a material that was hypoallergenic and antibacterial to minimize potential harm. However, through research we found that 'hypoallergenic' is not defined by the US Food and Drug Administration (FDA) and companies that use that terminology define it in their own ways. We did find that it was common for people to have allergies to latex and nickel, and made sure that the band material we selected did not contain either. The band material would have to be abrasion and impact resistant, as it should not break off while it is used in triathlete activities. The material should also be temperature resistant in high or low temperatures as the environment that the athletes will carry the product could be in either condition. Other features that we considered were good skin feel, washability, and appealing shape and design. It was also important that it be affordable for it to be competitive in the market. We searched for materials that would conform to most of the needs mentioned and came to a conclusion that a durable elastomer material would be the most fitting. CES edupack was used to search for different types of elastomers with different properties.

For the band to connect to the housing, a metal bar mechanism made out of stainless steel was the most likely candidate when balancing strength, corrosion resistance, and cost. It was decided that the band and housing should be interchangeable, so the bar should be spring-loaded for ease of insertion and removal similar to watch pins to facilitate ease of repairs without introducing unknown failure points.

B. Housing (Qi)

Most important was ensuring the housing's ability to provide protection from solid objects and moisture to maintain functionality, measured by IP standards. High activity also warranted an impact resistant design that would pass our values for the Charpy impact test. The design of the housing also required that enough slots existed for a suitable number of sensors to fit. The weight of the housing would be a majority of the total weight due to necessity, but in order to still minimize the weight, a material with low density but high hardness was sought.

Even though low cost was not an essential user need, a cheap material was sought while not compromising on performance. The material was chosen to look modern, such as with metals and ceramics. It was decided that the housing would support six sensors at a time as a compromise between size and functionality. From our second user survey of triathletes and similar athletes, six sensor bays would be enough to satisfy the data collection needs of our primary market.

The screen glass had to meet the same requirements as the housing for the IP standards and impact tests. Safety of the screen glass was also important; for example, the glass should fracture into granules rather than large shards. Since there would be direct exposure to the environment, the screen also required high durability under water and in sunlight.

C. Electronics (Tony)

Above all, the electronic components needed to work properly and provide accurate data for the user, according to our revised top priority of functionality. Given our emphasis on the ability of our product to be lighter and more comfortable than alternatives, we also prioritized sensors with small form factors capable of fitting on a band similar to the size of those found on competitor products. After doing research into commercially available environmental and biometric sensors such as Maxdetect RHT03 relative humidity and temperature sensor [3], it was determined that size was not going to be an issue when selecting components, as most sensors are completely fabricated on tiny ICs with customizable breakout board sizes. With many sensors requiring skin contact, safety was also a large consideration, but because most sensors do not require high voltages to operate there was little concern of electric shock. Therefore, when selecting sensor sources, cost became the number one deciding factor, as all other parameters were relatively uniform within every sensor type.

With regard to the communication protocol between the sensors and the data collection module, wearability and durability were the two most relevant ITYs, as functionality and safety should be the same regardless of what was chosen. All commercially available communication protocols have well-documented and published standards to guarantee functionality and consumer safety, but direct wire communications was the solution with the lowest energy and dollar cost.

D. Energy Source (Hayley)

One of the main focuses of the battery selected was to provide enough energy throughout the user’s workout session. The battery life was determined by comparing the current fitness trackers available on the market with similar features. Since the battery life was dependent on the number of sensors loaded, the power draw of the sensors was also considered in determining the capacity of the battery. Other usability parameters such as charging time were also compared. Another factor that was taken into account was the weight of the battery. Since the user would be carrying the device at all times when being active, lightweightness was an import factor in designing our produce. Therefore, trade-off was made between lightweightness and battery capacity.

Besides supplying sufficient, stable energy to the device, the battery's main focus was safety since the device has direct contact with the user's skin. We were looking for a sustainable and safe battery source for our device, factoring in extreme environments the user could be in when doing activity.

IV. Material Selection

A. Band

After much research into different types of durable elastomer materials, the decision came down to two different types of elastomers: DuPont™ Hytrel TPC-ET thermoplastic elastomer and COHRlastic 9050. Both of the materials met the marginal values, however the COHRlastic 9050 had superior properties which would put it closer to the optimal values. Therefore, COHRlastic 9050 was chosen for the band material as costs were similar.

Fabric wear can be measured via different types of testing such as tensile strength, tear strength, and elongation strength testing. COHRlastic 9050 has durometer of 50 Shore A (unit). The tensile strength (ASTM D412) is 900 psi and the tear strength (ASTM D624 Die B) is 75 ppi. The elongation (ASTM D412) is 400%. COHRlastic has a very large temperature range of -100F to 500F. These test values indicated that the band material would be extremely durable and appropriate for use in extreme conditions which would be favorable for the athletes in various training environments. Also this material was found to be chemically inert, fungus resistant, and ozone/UV resistant. Since there is no FDA definition of 'hypoallergenic' we made sure that the material was at least antibacterial and does not include latex.

The product is manufactured in continuous length form of 36". Standard thicknesses available include 1/32'', 1/16", and 1/8". However, other thicknesses can be ordered as a special request. The thickness chosen for our band was 1/8" to provide appropriate durability.

In order to verify whether the material was suitably lightweight, the mass of COHRlastic 9050 used in the band was calculated.

$$Mass\ of\ band\ (1/8"\ thickness) = 14.7g/in^2 * 0.75in(width) * 6in(length) = 66.15g/band$$

In order to verify whether the material was suitably cost effective, the price of COHRlastic 9050 used in the band was calculated.

$$Price\ per\ 1\ roll(36\ in * 5\ yds) = \$867.73$$
$$Price\ per\ 1\ in^2 of\ band\ material = \$0.134$$
$$Price\ per\ 1\ band = 0.134 * 0.75 * 6 = \$0.603$$
$$Price\ for\ 1000\ pieces = \$603$$

Stainless steel 316L was chosen for the bar connection. 316L provides a good compromise between cost, strength, and corrosion resistance compared to other grades of stainless steel. Its widespread use in watches proves its popularity as a wearable material [4].

B. Housing Material

COHRlastic 9050 was initially proposed as the housing material also. However, its tensile strength of 900 psi and elongation in the ASTM D412 test of 400% raised some concern about its ability to protect against shock. Compared to the tensile stress, yield stress, elongation, and hardness of materials used in the housing of watches [5], the selected elastomer was not strong enough to protect the inside circuit, especially during intense activity. Zirconia, $ZrO2$, was then selected as the housing material after inspecting suitable candidates from CES EduPack. Table A6, copied from CES eduPack, shows the properties of zirconia. A range of values exists due to its availability in unstable, stable, and partially stable allotropes. The price of zirconia is 12.2 usd/lb, which is relative higher than the elastomer, but the thermal, tensile, and hardness properties are much better. The tensile strength of zirconia 72.5-103 ksi, and its compressive strength is 522-754 ksi. Zirconia also has high durability and scratch resistance. There also exist a few recycling plants in the US which can process and repurpose used zirconia, which made it a good choice from a DFS viewpoint. Alternatively, an elastomer coating could be applied on the housing surface to protect the housing from chipping, and should the surface coating become damaged, the zirconia housing could be refurbished by sending it back to us for a recoating.

In order to verify whether the material was suitably lightweight, the mass of zirconia used in the housing was calculated. The density of zirconia is 368 lb/ft^3. According to our drawing,

$$Volume\ of\ housing = 0.4\ in^3 = \frac{0.4}{12^3} ft^3 = 0.00023148\, ft^3$$

Therefore, the mass of the zirconia housing is

$$Mass\ of\ housing\ =\ 368\ lb/ft^3 * 0.00023148\, ft^3 = 0.0893\ lb = 40.5\ g$$

and the price for 1000 pieces of housing is

$$Price\ of\ 1000\ pieces\ =\ 0.0893\ lb\ * 12.2\ usd/lb\ * 1000 = 1089\ USD.$$

1. Display Screen

Gorilla glass is commonly used in smartphones screens, and for good reason. Figure A6 indicates the specifications of gorilla glass. The area of gorilla glass required for each device was 1.5 in^2. The price for Gorilla glass per square meter is 44.8 USD from alibaba.com. Gorilla glass has a high durability and a much lower price than sapphire display. It has comparatively high Young's modulus, hardness, fracture toughness, chemical durability, and also scratch-resistance as cover glass. According to the article from the CORNING official website [6], their gorilla glass 4 is used in the Samsung Galaxy smartphone because of its better performance over competitors' glass when dropped on rough surfaces. For its proven service in the consumer market, gorilla glass was chosen as our screen material.

C. Electronics Materials and Selections

The following list of sensors in Table 3 was determined to be relevant to most users for a variety of sports and activities, not just those included in our primary market:

Table 3. Sensor Varieties

Temperature
3-Axis Accelerometer
Blood Oxygen
Radiation
Pedometer
Pulse
Myoelectric
Humidity
Blood Pressure
GPS
Altimeter
Hall Sensor
Proximity
Pressure
Photocell

The sensors chosen were determined by doing market research on sparkfun.com, a popular consumer-oriented electronics hardware online store. Their sensors were first sorted by best-selling, then filtered by increasing size. 15 sensor types, an amount reaching our optimal value for number of available sensors, were chosen to provide variety to the consumer while not introducing feature creep to a product that has not been fully realized yet. Sorting by increasing size also guaranteed sensors which would fit into the housing's sensor bays. Due to sourcing the sensors from outside manufacturers, a uniform form factor was needed to ensure compatibility with the housing and wired communication system. It was decided that custom breakout boards would be manufactured from FR-4 glass epoxy and copper wiring. These materials were chosen due to their prevalence and standardization in the electronics industry, meaning costs would remain low for mass production.

A five wire USART system for communication between sensors and storage and power was selected:

V+, V-, GND, CLOCK, DATA

With this design choice, every sensor bay in the housing would have these wires available for the sensors to access. Focusing on a larger picture with respect to the housing, data is wired to a central cpu and microSD located between the sensor bays and screen for data storage. Firmware present with the CPU allows for “hot swapping” of sensors. The user is able to switch sensors while the device is on and immediately start logging data. Every sensor is placed in a uniform bay designed to be thermally regulated and protected from water intrusion. Silicone gaskets are present on each sensor, which provide water-proofing, the same system used on high end flashlights such as the Fenix PD35, rated at IPX-8 [7]. With the seal being water-tight, dust is also prevented from entry, giving an IP-68 rating which matches our optimal value for environmental protection. Sensor dummies made out of silicone are also provided should fewer than six sensors be needed for an application. These dummies will fill empty slots to provide both comfort against the skin and environmental protection without adding undue weight.

To guarantee temperature regulation of the sensors, a worst-case heat transfer calculation was performed to check for compatibility. Assuming a worst-case upper bound on internal temperature using one-dimensional heat transfer, we calculated the internal wall temperature of the band from sensor power consumption. In reality, there are six walls conducting heat with the ambient environment. One of the walls is at skin temperature. An operating temperature close to room temperature should indicate accurate data collection in accordance with sensor datasheets, satisfying need number 8 on the needs-metrics matrix. Steady state conditions were chosen, and dimensions are explained in the relations below.

$$\dot{Q}_{cond,wall} = kA\frac{T_1 - T_2}{L}$$

k = 1.7 (W/m.K) for zirconia

A = 0.0001161288 m^2

T_2 = 25C

L = 0.004572 m through to the surface of housing opposite skin

Q’ = 0.0882 W value from 14 mA at 6.3 V (assuming 100% conversion from electrical energy to heat) for the high consumption MyoWare sensor [8]

$$T_1 = 27\ C$$

Even under the worst case scenario where all energy supplied is converted to heat and only one wall is available for heat transfer, the interior wall temperature would only be 2 C higher than ambient, well within operating range. In fact, with human skin at 37C, the band will not feel significantly different from stagnant air.

The dimensions of each sensor bay are 0.3 x 0.3 x 0.25 inches, yielding a volume of 0.37

cm^3 each. Given six sensor bays per housing, each housing has 2.21 cm^3 of space. Assuming half the space is filled with FR-4 glass epoxy, we can calculate the approximate mass of six sensors. The density of FR-4 glass epoxy is 1.9g/cm^3 [9] which yields a total sensor mass of 2.1 g/bay.

Sensors may be priced based on their complexity, as complexity is proportional to manufacturing costs. Prices of simple ADXL335 3-Axis accelerometers are currently $1.70 each on bulk-retailer aliexpress.com. Prices of the complex AD8232 single lead heart rate sensor are $18.98 each. We assumed that the average cost of a sensor was $10.34, the average of the two, for quantities under 1,000. Assuming a modest discount of 10% for orders of at least 10,000, because chip manufacturing is already highly optimized, the price per chip would then be $9.31.

D. Battery Material

As shown in Table 4, commercially available fitness trackers have a battery life ranging from a few days to one year, depending on the power consumption rate and battery type. Generally, non-rechargeable batteries are used with devices that require less power and last at least half a year. Devices that use rechargeable batteries usually have more features such as GPS and heart rate tracking and need to be recharged every 6 -10 days. By frequency, coin cell batteries are the most favored type due to their small profile and lightweightness and are used in the majority of the current fitness tracking products.

Table 4. Commercially Available Fitness Tracker Battery Type and Battery Life

Product	Battery Type	Battery Life
Garmin Vivofit	CR1632	1 year
Misfit Shine	CR2032	6 months
Jawbone UP	CR2032	1 month
Moov	CR2032	6 months
Fitbit Zip	CR2025	6 months
Garmin Vivoactive	Li-ion	10 days
Fitbit Surge	Li-polymer	7 days with GPS, 10 days without GPS
Polar Loop	Li-polymer	6 days

Blue Highlight – devices with non-rechargeable battery
Yellow Highlight – devices with rechargeable battery

A lithium-Polymer (LiPo) battery was chosen as the energy source for our product due to its efficiency, improved safety, low profile, flexible form, and lightweightness. It is located behind the glass screen along with the memory and cpu for easy access. The entry hatch is lined with silicone to meet IP-68 standards. LiPo batteries, though having similar charge/discharge characteristics similar to that of a Li-ion battery, replace the traditional porous separator with microporous electrolyte. They also flexible and do not need a rigid case like Li-ion batteries do. Compared to other types of batteries, Li-Po batteries have higher energy density and are sleeker and thinner, which contribute to lightweightness, one of the important user needs. Just like other types of batteries, certain stores take Li-Po batteries in for recycling. Otherwise, Li-Po is easy to dispose of compared to other types of batteries. It only needs to be completely discharged and immersed in salt water before placing it in regular trash.

Recent research has shown that using membranes with small pore sizes in LiPo batteries increase their safety. Other safety features include using a sandwiched structure of two layers of polypropylene (PP) with one layer of polyethylene (PE) in between. With an operating temperature less than 140C, which is above the melting temperature of PP, this structure can still effectively prevent meltdown of the membrane [10]. The standard industry battery protection feature of using a charge controller will prolong battery life and protect the safety of the user. We will also be using a lithium ion “intercalating” anode, i.e. a compound capable of accepting lithium ions in its lattice and electrons in its electronic structure. During the operating process, the cell will experience only a movement of ions without deposition of lithium metal, greatly reducing the risk of malfunction and/or unexpected side reactions [11].

Other types of battery that were considered include Lithium Cobalt and $LiMn_2O_4/LiFePO_4$ batteries, but both have certain constraints. LiCo batteries have high capacities but are prone to exploding, have slow recharge rates, and are expensive, making them less qualified for our purposes since the product will be mass manufactured and charging rate is an essential factor for everyday electronic devices. $LiMn_2O_4/LiFePO_4$, having higher specific power and long life, also have lower capacity rendering them unsuitable for this product.

For our product, accounting for power usage of all sensors with an ideal battery life of 10 days and marginal life of 7 days. A battery with a capacity of 1000mAh would fulfill the need of 10 days of 24 hours continuous tracking and one hour workout per day with all sensors loaded. Charging time is only 90 minutes until full. Currently available batteries on the market that suit our needs cost $10-20 per piece and weigh 30g.

V. Manufacturing Specifications

A. Design for Sustainability

A DFS matrix from the 3M corporation was used as reference for our DFS matrix design. Table A7, the DFS matrix, shows the sustainability of our product, including its effect on environment, health, energy and resource use during the processes of material acquisition, manufacturing operations, and customers use. A rating of 1 in the table means the impacts and risks of a process under a given condition are known. Regarding material acquisition, all components of our product are ordered from other companies. Thus, the process of material acquisition involves only the ordering and delivery of our materials. Manufacturing processes include assembly of components and transport of complete products. These operations are limited to reshaping of glass and elastomer materials. Most of the materials used in our product can be recycled or reused, but the recycling process for different types of sensors is unclear as their variety make it difficult to lump them all into one process. Our product favors late-stage assembly, as the user should customize his or her own sensor package.

B. Industrial Design

Table A8 shows the industrial design considerations of our product, including its ergonomics and aesthetics. There are five aspects considered in ergonomics, namely ease of use, ease of maintenance, quantity of user interactions, novelty of user interactions, and safety. Functionality was considered the most important, earning it a rating of 9. Explanations for each aspect are listed in the chart.

C. Manufacturing

Table 5 below is our bill of materials. We calculated the cost of materials required for making 1000 pieces of our product and the mass for each component and total per product. There is usually a discount for larger amount purchases, so the cost of 10,000 pieces is also calculated with an assumed 10% discount per piece.

Table 5. Bill of Materials

	Component	Price/piece (USD)	Price per 1,000 pieces (USD)	Price per 10,000 pieces (USD)	Mass per piece (g)
Housing	Zirconia	1.08 / 0.98	1,089	9,801	40.5
	Gorilla Glass	0.044 / 0.04	44	396	2
Band	COHRlastic 9050	0.603 / 0.60	603	6,027	66.2
Sensors	Varied based on types	10.34 / 9.31	10,340 on average	93,060 on average	2.1 on average
Battery	Lithium-Polymer (LiPo)	10 / 9.10	10,000	91,000	30
Total		$22.10 / $20.02	$22,076	$199,284	147.1g (assuming three sensors)

VI. Final Product

Introducing:
Bandit - “Take What You Need”

A three dimensional concept sketch is included below in Figure 1 as a demonstration of our minimal viable product. The band is adjustable via a strap with a buckle and discrete sizing holes. The band interfaces with the housing via removable spring-loaded pins which allow the housing several mounting options similar to current active sports cameras to satisfy the use cases for our secondary market. When worn on the body, the short 1.5 inch width of the housing maximizes skin contact for all six sensors loaded. The touch screen opposite the sensor bays facilitates quick status checks at a glance. Any inputs made are available by gestures and button presses on the screen. An energy-saving mode disables the screen and maximizes data collection time by reducing battery drain. The athlete is offered a seamless user experience without the need for an external mobile device to collect data.

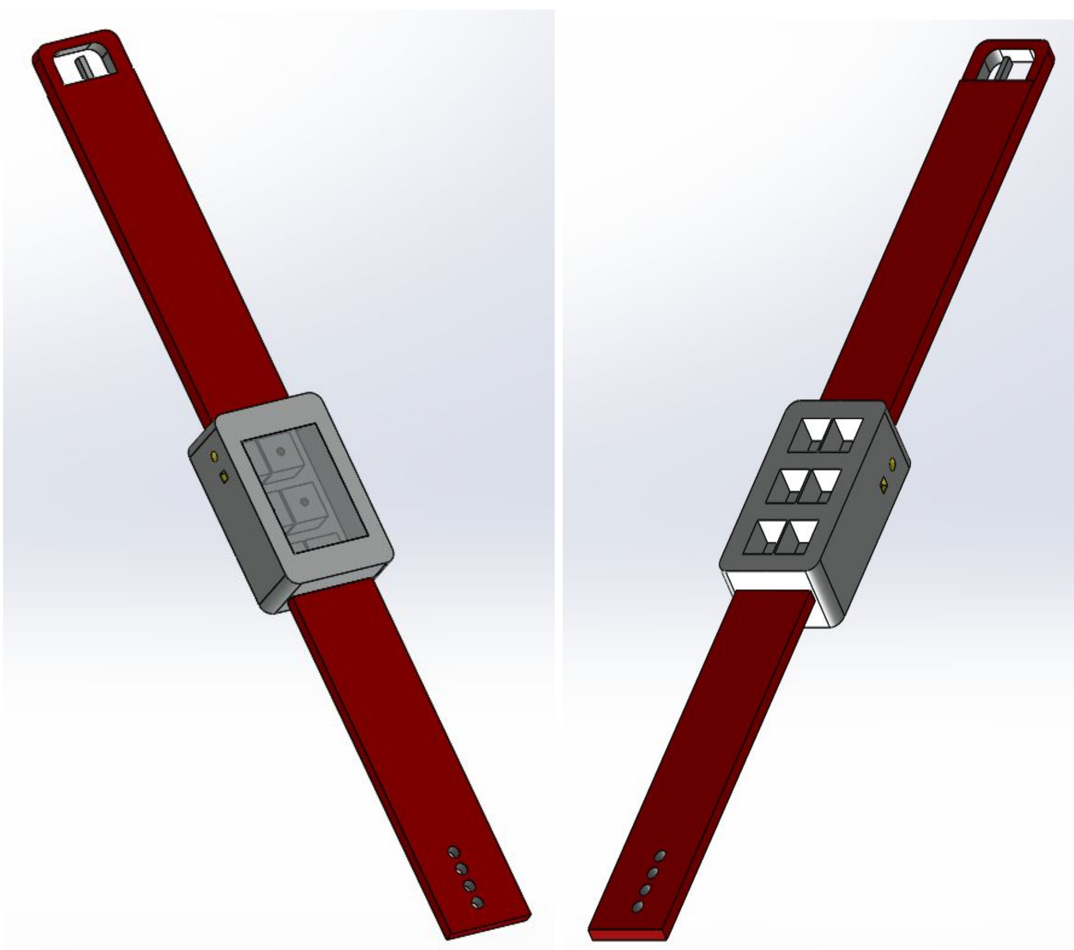

Figure 1. Bandit Front and Rear Views

Figure 2 provides dimensional specifications for the housing.

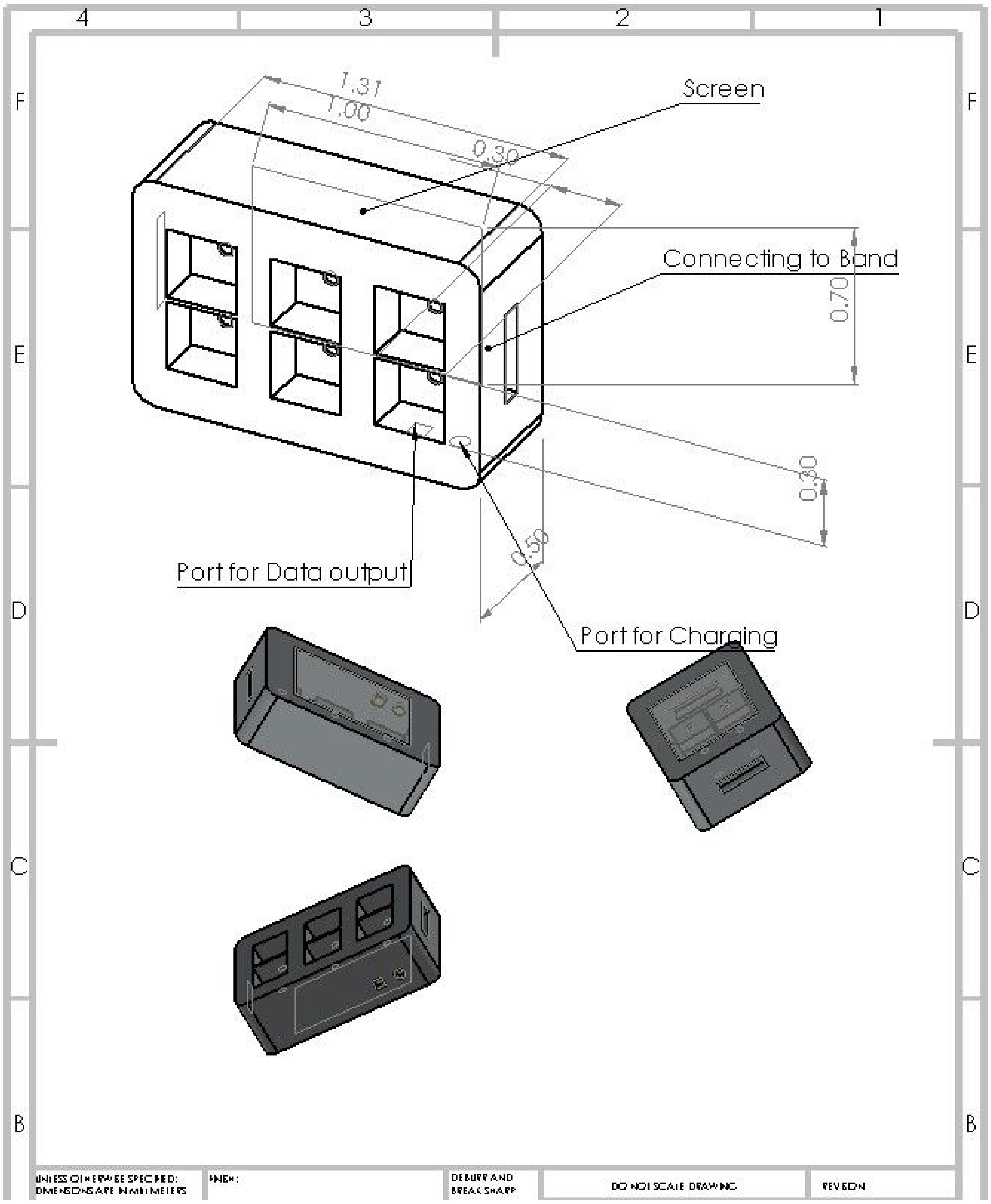

Figure 2. Housing Assembly with Dimensions Labelled in Inches

Given the opportunity to further develop this product, we would continue to iterate the material selection process to reduce the weight. A hardware prototype implementation using the Java code written in Table A9 would also be fully implemented to test sensor functionality and switching. Feedback from our primary market would be taken at every concept iteration to gauge reaction to design choices. Testing and refinement tests to measure reliability and life would allow us to then develop a sales plan complete with promotional materials to round out our concept development.

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Appendix

Dear Jessica,

The thermoelectric device can generate electricity from body heat. However, the energy from body heat is not that much.
So, the generated electricity using body heat is not enough to charge batteries for mobile phone.
It can be used only for charging sensors for health care or IOT.

It is not a matter of size, but of power consumption. Currently, typical smart watch consumes 30mW in average. Thermoelectric device can generate the power of 30 uW/cm2 from human body. If we make the thermoelectric generator of 10cm x 10 cm, it can generate 3 mW from human body. Medical sensors or other sensors consume less than 1mW. So, TEG will be enough only for sensor operation if we use human body as the heat source. Hope this help you in your project.

Best Regards
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****

Figure A1. Interview with Dr. Cho on his wearable TEG

Interview with DGIST Dr. Hong

1. What is the most important thing for quality batteries?

=> Every part of the battery is important for the performance of batteries. The electrode materials and electrolyte as well as the packaging all have to be compatible with each other and all parts matter for the battery to have high quality.

2. What would be the biggest concern for batteries in colder weather?

=> Li-ion batteries work from the electrochemical reaction between the electrodes and the electrolytes. However, in cold weathers the electrochemical reactions tend to not be as reactive (or slower reaction rate). When it's too cold, the reactions do not go all the way which decreases the capacity. So it will not charge fully and discharge fully either. It is important that a device(or battery) is in a certain range of temperature where it can actively charge and discharge. The range depends on the material of the battery (basically case by case).

3. What do you recommend that would be a good battery to use in these temperatures?

=> I am not an expert in the industry of what companies sell, however, most batteries that are commercially used do work fine in cold weathers, it just doesn’t have the FULL capacity as it would in regular weathers.

4. What do you suggest we do to improve the battery quality even in cold weather?

=> Make sure the device does not get too cold for the materials inside to have a low electrochemical reaction rate.

Figure A2. Interview with Dr. Hong on Secondary Batteries

Table A1. Prioritization Matrix for Commercially Available Activity Trackers

	Lightweight	Durable	Comfortable	Price	Raw	Normalized
Lightweight		10	10	5	25	0.72
Durable	0.1		5	1	6.1	0.18
Comfortable	0.1	0.2		1	1.2	0.03
Price	0.2	1	1		2.2	0.06
				Total	34.5	1.00
Lightweight	Node +	Tempo Trainer	ICEdot Crash Sensor	Lazer Genesis LifeBEAM	Raw	Normalized
Node +		10	5	1	16	0.46
Tempo Trainer	0.1		5	1	6.1	0.18
ICEdot Crash Sensor	0.2	0.2		10	10.4	0.30
Lazer Genesis LifeBEAM	1	1	0.1		2.1	0.06
				Total	34.6	1.00
Durable	Node +	Tempo Trainer	ICEdot Crash Sensor	Lazer Genesis LifeBEAM	Raw	Normalized
Node +		5	10	1	16	0.54
Tempo Trainer	0.2		1	0.2	1.4	0.05
ICEdot Crash Sensor	0.1	1		5	6.1	0.21
Lazer Genesis LifeBEAM	1	5	0.2		6.2	0.21
				Total	29.7	1
Comfortable	Node +	Tempo Trainer	ICEdot Crash Sensor	Lazer Genesis LifeBEAM	Raw	Normalized
Node +		0.2	0.1	1	1.3	0.03
Tempo Trainer	5		1	10	16	0.36
ICEdot Crash Sensor	10	1		5	16	0.36
Lazer Genesis LifeBEAM	1	10	0.2		11.2	0.25
				Total	44.5	1.00
Price	Node +	Tempo Trainer	ICEdot Crash Sensor	Lazer Genesis LifeBEAM	Raw	Normalized
Node +		10	5	1	16	0.53
Tempo Trainer	0.1		1	5	6.6	0.22
ICEdot Crash Sensor	0.2	1		5	6.2	0.21
Lazer Genesis LifeBEAM	1	0.2	0.2		1.4	0.05
				Total	30.2	1.00

Total	Lightweight	Durable	Comfortable	Price	Raw	Normalized
Node +	0.333	0.097	0.001	0.032	0.463	0.467
Tempo Trainer	0.127	0.008	0.011	0.013	0.159	0.161
ICEdot Crash Sensor	0.216	0.037	0.011	0.012	0.276	0.279
Lazer Genesis LifeBEAM	0.044	0.038	0.008	0.003	0.092	0.093
				Total	0.990	1.00

Safety

- Battery stability in various environments
- Non-constrictive
- Compliant with electronics regulations

Functionality

- Usable with any biometric and environmental sensor already existing
- Independent data collection from any backing mobile apps
- Ability to swap out sensor packages and battery packs
- Plethora of mounting solutions (a la GoPro)

Usability

- Straightforward interface, set up and go
- Lightweight
- Usable in a large range of temperatures
- Easy to take on/off
- Unobtrusive when user is moving
- Highly accurate data

Durability

- Water proof
- Abrasion resistant
- Impact resistant
- UV resistant
- Easily repaired

Wearability

- Touches skin directly, hypoallergenic
- Comfortable, easily adjustable
- Odor free
- Quick drying
- Washable
- Anti-bacterial
- Small and Lightweight

Aesthetics

- Customizable appearance
- Modern design
- Statement of personality

Affordability

- Consumers decide which features they need and are able to purchase components separately

Novelty

- Integration with cameras, mics
- Potential everyday living companion

Figure A3. Initial ITYs Ranking

Table A2. Needs-Metrics Matrix

	Mass vs. other products	IP Standards Testing	Fabric Wear Tests	Impact Tests	Number of sensors within size limit	Time taken to put on	Subjective user experience ratings	Subjective user experience ratings compared to other products	Fabric softness tests	Change in data accuracy and battery temperature over a temperature range	Precision of reported data	Battery life under different sensor loads	Total data storage size and time until full	Hypoallergenic tests, pressure exerted by band, radiation testing	Subjective user feedback	Relative cost compared to other products	Dislocation upon exercise	Standard antibacterial tests	Time until dry from fully wet
Lightweight	x																		
Waterproof		x																	
Durable			x	x															
Modular sensor design					x														
User-friendly						x	x												
Comfortable								x	x										
Temperature resistant										x									
Accurate data											x								
Long battery life												x							
Adequate data storage													x						
Safe for the user														x					
Instills pride															x				
Looks modern															x				
Affordable																x			
Immobile																	x		
Anti-bacterial																		x	
Quick-drying																			x

Table A3. Ideal and Marginal Values

Metric No.	*Needs. No*	*Metric*	*Importance*	*Units*	*Marginal Values*	*Ideal Values*
1	2	Mass		g	<150	<100
2	2	Mass vs. Other products	3	%	100	<100
3	3	IP Standards Testing	4	IP (Ingress Protection)	68	68
4	4	Fabric Wear Tests	4			
5	4	Impact Tests	4	J (Joules)	120	150
6	5	Number of sensors within size limit	5	Sensors able to be fitted within given volume	10	15
7	6	Time taken to put on	3	s	20	10
8	6	Subjective user experience ratings	4	List	Given the product, the user would use it to train	The use looks forward to using the product and tells his or her friends.
9	7	Subjective user experience ratings compared to other products	4	List	"I don't notice it when I'm moving."	"I can hardly feel it."
10	7	Fabric softness tests	3	MIU (coefficient of friction)	MIU = 0.163	MIU = 0.273
11	8	Change in data accuracy and battery temperature over a temperature range	5	Error %	Extreme temperature 20	10
12	9	Precision of reported data	5	Error % compared to real data	10	5

13	10	Battery life under different sensor loads	4	days	10 days with maximum amount of sensors	7 days with maximum amount of sensors
14	11	Total data storage size and time until full	4	days	detailed information for 5 days, daily summaries of up to 14 days	detailed information for 7 days, daily summaries of up to 30 days
15		Hypoallergenic tests, pressure exerted by band, radiation testing	3	FDA Testing for Skin Sensitization to Chemicals - modified Draize-95 test	0.5	0
16	13,14	Subjective user feedback	5	List	Medium pride, looks morden	High pride, Looks modern
17	15	Relative cost compared to other products	4	US$	<5	<10
18	16	Dislocation upon exercise	3	mm	<6	<4
19	17	Standard antibacterial tests	2	min	<60	<90
20	18	Time until dry from fully wet	3	hr	<5	<2

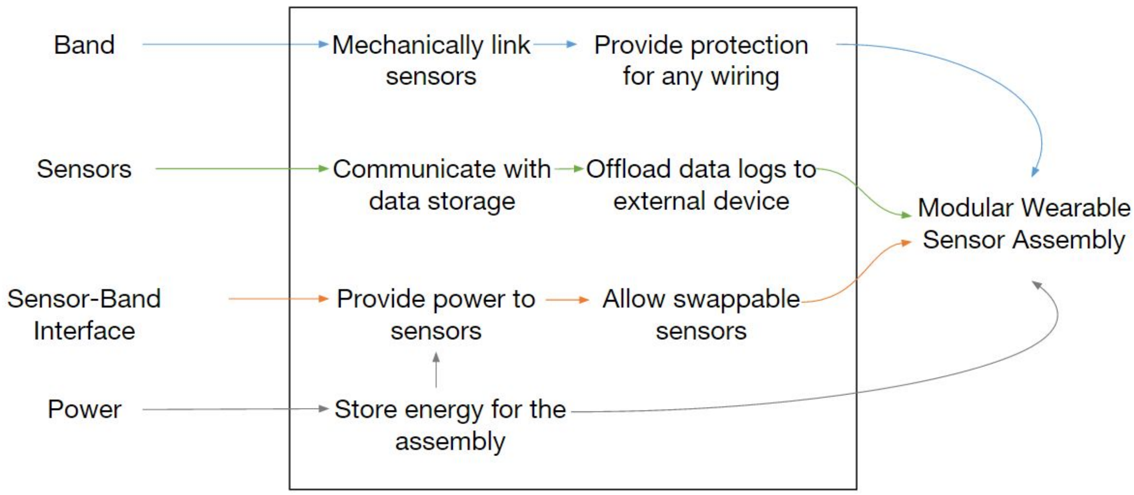


Figure A4. Function Diagram

<u>Band</u>

- Al Alloy
- Silicon Rubber
- Nylon Webbing
- Thermoplastic
- Steel Linkage
- Leather
- Composite

<u>Sensors</u>

- Bluetooth
- Near Field Communication
- USART/UART
- Wi-Fi
- Radio
- Micro-USB

<u>Sensor-Band Interface</u>

- Sliding Metal Bar

- Socket Enclosure

- Clip-on Design

<u>Power</u>

- Li-ion Battery
- Thermoelectric Generator with backup battery
- Triboelectric Generator with Backup Battery
- Button Cell
- Lithium Polymer

Figure A5. Concept Component Selection

Table A4. Initial Concept Scoring

	Concepts					
Selection Criteria	A	B	C	D	E	F
Ease of handling	0	+	+	0	+	-
Comfort	0	-	0	0	-	+
Ease of Manufacture	0	-	0	1	0	-
Durability	0	+	0	-	+	-
Battery Life	0	+	+	0	0	-
Net Score	0	1	2	0	1	-3
Continue?	No	Yes	Combine with D	Combine with C	Yes	No

Table A5. Concept Scoring Matrix

		Concepts									
		Reference (Fitbit)		B		CD		E		Tattoos	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Availability of Functions	30%	2	0.6	5	1.5	5	1.5	5	1.5	2	0.6
Comfort	25%	3	0.75	4	1	3	0.75	3	0.75	5	1.25
Power Safety	20%	3	0.6	3	0.6	2	0.4	3	0.6	2	0.4
Ease of Manufacture	10%	3	0.3	2	0.2	2	0.2	4	0.4	2	0.2
Durability	10%	2	0.2	2	0.2	2	0.2	4	0.4	1	0.1
Battery Life	5%	3	0.15	3	0.15	5	0.25	3	0.15	2	0.1
	Total		2.6		3.65		3.3		3.8		2.65
	Rank		5		2		3		1		4
	Continue?		No		No		No		Yes		No

Table A6. Properties of Zirconia

General properties

Density	368	-	384	lb/ft^3
Price	* 8.46	-	12.2	USD/lb
Date first used	1962			

Mechanical properties

Young's modulus	29	-	36.3	10^6 psi
Shear modulus	* 8.7	-	12.5	10^6 psi
Bulk modulus	* 23.2	-	30.7	10^6 psi
Poisson's ratio	0.3	-	0.32	
Yield strength (elastic limit)	72.5	-	103	ksi
Tensile strength	72.5	-	103	ksi
Compressive strength	* 522	-	754	ksi
Elongation	0			% strain
Hardness - Vickers	1e3	-	1.23e3	HV
Fatigue strength at 10^7 cycles	* 43.5	-	72.5	ksi
Fracture toughness	5.46	-	7.28	ksi.in^0.5
Mechanical loss coefficient (tan delta)	* 5e-4	-	0.001	

Thermal properties

Melting point	4.62e3	-	4.89e3	°F
Maximum service temperature	2.19e3	-	2.73e3	°F
Minimum service temperature	-459			°F
Thermal conductor or insulator?	Poor insulator			
Thermal conductivity	1.16	-	2.43	BTU.ft/h.ft^2.F
Specific heat capacity	0.115	-	0.124	BTU/lb.°F
Thermal expansion coefficient	5.83	-	6.11	µstrain/°F

Electrical properties

Electrical conductor or insulator?	Good insulator			
Electrical resistivity	2e18	-	3e21	µohm.cm
Dielectric constant (relative permittivity)	12	-	25	
Dissipation factor (dielectric loss tangent)	* 8e-4	-	0.002	
Dielectric strength (dielectric breakdown)	* 102	-	152	V/mil

Thermal properties

Melting point	4.62e3	-	4.89e3	°F
Maximum service temperature	2.19e3	-	2.73e3	°F
Minimum service temperature	-459			°F
Thermal conductor or insulator?	Poor insulator			
Thermal conductivity	1.16	-	2.43	BTU.ft/h.ft^2.F
Specific heat capacity	0.115	-	0.124	BTU/lb.°F
Thermal expansion coefficient	5.83	-	6.11	µstrain/°F

Electrical properties

Electrical conductor or insulator?	Good insulator			
Electrical resistivity	2e18	-	3e21	µohm.cm
Dielectric constant (relative permittivity)	12	-	25	
Dissipation factor (dielectric loss tangent)	* 8e-4	-	0.002	
Dielectric strength (dielectric breakdown)	* 102	-	152	V/mil

Durability: water and aqueous solutions

Water (fresh)	Excellent
Water (salt)	Excellent
Soils, acidic (peat)	Excellent
Soils, alkaline (clay)	Excellent
Wine	Excellent

CORNING
Gorilla® Glass

Corning® Gorilla® Glass 4 – Corning's latest composition was formulated to address breakage – the #1 consumer complaint, according to Corning's research. The new glass is just as thin and light as previous versions, but has been formulated to deliver dramatically improved damage resistance allowing improved in-field performance. Corning® Gorilla® Glass 4 has been tested for performance when subjected to sharp contact damage, such as asphalt and other real-world surfaces.

Product Information

Benefits

- Enhanced retained strength after use
- High resistance to scratch and sharp contact damage
- Improved drop performance
- Superior surface quality

Applications

- Ideal protective cover for electronic displays in:
  - Smartphones
  - Laptop and tablet computer screens
  - Mobile devices
- Touchscreen devices
- Optical components
- High strength glass articles

Dimensions

Thickness: 0.4 mm - 1.0 mm

Additional thicknesses available upon request.

Viscosity

Softening Point ($10^{7.6}$ poises)	912 °C
Annealing Point ($10^{13.2}$ poises)	646 °C
Strain Point ($10^{14.7}$ poises)	596 °C

Properties

Density	2.42 g/cm^3
Young's Modulus	65.8 GPa
Poisson's Ratio	0.22
Shear Modulus	26.0 GPa
Vickers Hardness (200 g load)	
Un-strengthened	489 kgf/mm^2
Strengthened	596 kgf/mm^2
Fracture Toughness	0.67 MPa m$^{0.5}$
Coefficient of Expansion (0 °C - 300 °C)	86.9 x 10^{-7}/°C

Chemical Strengthening

Capability of >850MPa CS, and >50 µmDOL

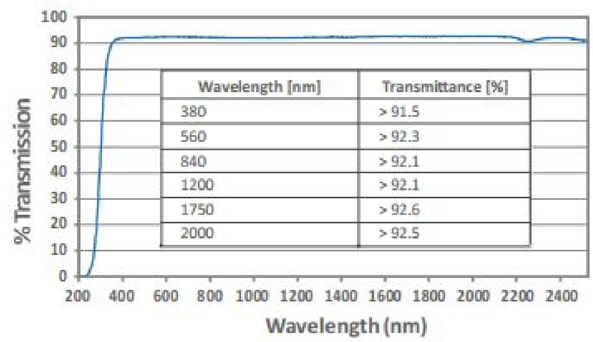
*Specifications subject to change

Optical

Refractive Index (590 nm)

Core glass**	1.49
Compression layer	1.51
Photo-elastic constant	30.3 nm/cm/MPa

*** Core index is used for FSM-based measurements since it is unaffected by ion-exchange conditions.*



Chemical Durability

Durability is measured via weight loss per surface area after immersion in the solvents shown below. Values are highly dependent upon actual testing conditions. Data reported is for Corning® Gorilla® Glass 4.

Reagent	Time	Temperature (°C)	Weight Loss (mg/cm^2)
HCl - 5%	24 hrs	95	34.7
NH_4F:HF - 10%	20 min	20	3.3
HF - 10%	20 min	20	39.4
NaOH - 5%	6 hrs	95	5.9

Electrical

Frequency (MHz)	Dielectric Constant	Loss Tangent
54	7.89	0.026
163	7.77	0.024
272	7.70	0.024
381	7.66	0.024
490	7.63	0.023
599	7.60	0.024
912	7.43	0.024
1499	7.39	0.025
1977	7.37	0.025
2466	7.34	0.026
2986	7.33	0.027

Terminated coaxial line similar to that outlined in NIST Technical Notes 1520 and 1355-R.

Figure A6. Properties of Gorilla Glass

Table A7. 3M DFS Matrix

DFS Matrix		Manufacturing Operations			Customer	
Impacts	Material Acquisition	Process	Packaging	Transport	Product Use, Reuse, Maintenance	Recycle, Final Disposal
Environment						
Air	1	1	1	3	1	1
Water	1	1	1	3	1	2
Solid Waste	1	1	1	3	1	2
Energy	1	1	1	1	1	1
Resource USE	1	1	1	1	1	1
Health						
Chemical	1	3	3	3	1	3
Physical	1	3	3	3	1	3
Biological	1	3	3	1	1	3
Safety						
Chemical	1	3	1	1	1	3
Electrical	1	3	1	1	1	3
Mechanical	1	3	1	1	1	3
1	Impacts understood and Risks adequately addressed					
2	Impacts understood and Risks require further attention					
3	Impacts/Risks not completely understood					
4	EH&S Advantage					

Table A8. Industrial Design Matrix

Industrial Design Chart		
Ergonomics	Importance of rating(from 1 to 10, 1 is the lowest, and 10 is the highest importance)	Explanation of Rating
Ease of Use	9	The device is considered to be used daily or each time people do sports; only needs on/off button. It should be easy to output data to smart phones apps.
Ease of Maintenance	3	Materials used for housing and band are cheap. Sensors are replaceable and inside electronics are not required for maintenance.
Quantity of User interactions	5	Users need turn on/off the device and read the data on the screen of the device. The device can automatically record data, but users may output the data collected to smart phones.
Novelty of User interactions	5	The device is designed to be easily used. Bluetooth can be used for data output. Reading the data displayed on the screen is simple and convenient.
Safety	8	Since the device may contact users' skin directly, safety is concerned in inside circuit (heat generation), skin harmless material.
Aesthetics	7	Somewhat important, but we believe functionality is more important among the fitness crowd
Product Differentiation	7	There are many types of performance trackers in the market, but ours have more functions than others. Even so, good appearance is still necessary for differentiation.
Pride of Ownership, fashion, or images	8	The device is considered to be frequently used and highly visible in public areas. Users desire a high pride when using it.
Team Motivation	8	Each of our team members takes charge of designing one part of the device. The creative design of each part can inspire the development of the complete form of the product.

Table A9. Java Grafica API Implementation

```
import grafica.*;
import java.util.Random;
import processing.serial.*;

PFont font;
Scrollbar scaleBar;

int Sensor;      // HOLDS PULSE SENSOR DATA FROM ARDUINO
int IBI;         // HOLDS TIME BETWEN HEARTBEATS FROM ARDUINO
int BPM;         // HOLDS HEART RATE VALUE FROM ARDUINO
int[] RawY;      // HOLDS HEARTBEAT WAVEFORM DATA BEFORE SCALING
int[] ScaledY;   // USED TO POSITION SCALED HEARTBEAT WAVEFORM
int[] rate;      // USED TO POSITION BPM DATA WAVEFORM
float zoom;      // USED WHEN SCALING PULSE WAVEFORM TO PULSE WINDOW
float offset;    // USED WHEN SCALING PULSE WAVEFORM TO PULSE WINDOW
color eggshell = color(255, 253, 248);
int heart = 0;   // This variable times the heart image 'pulse' on screen
//  THESE VARIABLES DETERMINE THE SIZE OF THE DATA WINDOWS
int PulseWindowWidth = 490;
int PulseWindowHeight = 512;
int BPMWindowWidth = 180;
int BPMWindowHeight = 340;
boolean beat = false;


public GPlot plot1, plot2, plot3, plot4;

public Serial myPort;
public float xPos = 0;
public float humidity;
public float temperature;
public float acceleration;

boolean timeForHeart = false;
boolean notSetUp = true;

public void setup() {
  size(640, 480);

  myPort = new Serial(this, Serial.list()[5], 115200);
  myPort.bufferUntil('|');


  // Setup for the first plot

  plot1 = new GPlot(this);
  plot1.setPos(0, 0);
  plot1.setYLim(0, 100);
  plot1.setDim(220, 180);
  plot1.getTitle().setText("Relative Humidity");
  plot1.getXAxis().getAxisLabel().setText("Time");
  plot1.getYAxis().getAxisLabel().setText("Relative Humidity");
  plot1.setLineColor(color(200, 200, 255));
```

```
  // Setup for the second plot
  plot2 = new GPlot(this);
  plot2.setPos(320, 0);
  plot2.setDim(220, 180);
  plot2.setYLim(20,30);
  plot2.getTitle().setText("Temperature");
  plot2.getXAxis().getAxisLabel().setText("Time");
  plot2.getYAxis().getAxisLabel().setText("Temperature (C)");
  plot2.setLineColor(color(150, 150, 255));


  // Setup for the third plot
  plot3 = new GPlot(this);
  plot3.setPos(160, 230);
  plot3.setDim(220, 180);
  plot3.setYLim(-3, 3);
  plot3.getTitle().setText("Z Acceleration");
  plot3.getYAxis().getAxisLabel().setText("g");
  plot3.getYAxis().getAxisLabel().setTextAlignment(RIGHT);
  plot3.setLineColor(color(100, 190, 200));

  // Setup the mouse actions
  plot1.activatePanning();
  plot1.activateZooming(1.2, CENTER, CENTER);
  plot1.activatePointLabels();
  plot2.activateZooming(1.5);
  plot3.activateCentering(LEFT, GPlot.CTRLMOD);

}


public void draw() {
  if (timeForHeart && notSetUp) {
      size(700, 600);  // Stage size
  frameRate(100);
  font = loadFont("Arial-BoldMT-24.vlw");
  textFont(font);
  textAlign(CENTER);
  rectMode(CENTER);
  ellipseMode(CENTER);
// Scrollbar constructor inputs: x,y,width,height,minVal,maxVal
  scaleBar = new Scrollbar (400, 575, 180, 12, 0.5, 1.0);  // set parameters for the scale bar
  RawY = new int[PulseWindowWidth];          // initialize raw pulse waveform array
  ScaledY = new int[PulseWindowWidth];       // initialize scaled pulse waveform array
  rate = new int [BPMWindowWidth];           // initialize BPM waveform array
  zoom = 0.75;                               // initialize scale of heartbeat window

// set the visualizer lines to 0
 for (int i=0; i<rate.length; i++){
    rate[i] = 555;      // Place BPM graph line at bottom of BPM Window
   }
 for (int i=0; i<RawY.length; i++){
    RawY[i] = height/2; // initialize the pulse window data line to V/2
 }
  myPort = new Serial(this, Serial.list()[5], 115200);
```

```
  myPort.clear();            // flush buffer
  myPort.bufferUntil('\n');  // set buffer full flag on receipt of carriage return
 notSetUp = false;
}

  if (timeForHeart) {
    background(0);
  noStroke();
// DRAW OUT THE PULSE WINDOW AND BPM WINDOW RECTANGLES
  fill(eggshell);  // color for the window background
  rect(255,height/2,PulseWindowWidth,PulseWindowHeight);
  rect(600,385,BPMWindowWidth,BPMWindowHeight);

// DRAW THE PULSE WAVEFORM
  // prepare pulse data points
  RawY[RawY.length-1] = (1023 - Sensor) - 212;   // place the new raw datapoint at the end of
the array
  zoom = scaleBar.getPos();                      // get current waveform scale value
  offset = map(zoom,0.5,1,150,0);                // calculate the offset needed at this scale
  for (int i = 0; i < RawY.length-1; i++) {      // move the pulse waveform by
    RawY[i] = RawY[i+1];                         // shifting all raw datapoints one pixel left
    float dummy = RawY[i] * zoom + offset;       // adjust the raw data to the selected scale
    ScaledY[i] = constrain(int(dummy),44,556);   // transfer the raw data array to the scaled
array
  }
  stroke(250,0,0);                               // red is a good color for the pulse waveform
  noFill();
  beginShape();                                  // using beginShape() renders fast
  for (int x = 1; x < ScaledY.length-1; x++) {
    vertex(x+10, ScaledY[x]);                    //draw a line connecting the data points
  }
  endShape();

// DRAW THE BPM WAVE FORM
// first, shift the BPM waveform over to fit then next data point only when a beat is found
 if (beat == true){   // move the heart rate line over one pixel every time the heart beats
   beat = false;      // clear beat flag (beat flag waset in serialEvent tab)
   for (int i=0; i<rate.length-1; i++){
     rate[i] = rate[i+1];                  // shift the bpm Y coordinates over one pixel to the left
   }
// then limit and scale the BPM value
   BPM = min(BPM,200);                     // limit the highest BPM value to 200
   float dummy = map(BPM,0,200,555,215);   // map it to the heart rate window Y
   rate[rate.length-1] = int(dummy);       // set the rightmost pixel to the new data point value
 }
 // GRAPH THE HEART RATE WAVEFORM
 stroke(250,0,0);                          // color of heart rate graph
 strokeWeight(2);                          // thicker line is easier to read
 noFill();
 beginShape();
 for (int i=0; i < rate.length-1; i++){    // variable 'i' will take the place of pixel x position
   vertex(i+510, rate[i]);                 // display history of heart rate datapoints
 }
 endShape();

// DRAW THE HEART AND MAYBE MAKE IT BEAT
```

```
  fill(250,0,0);
  stroke(250,0,0);
  // the 'heart' variable is set in serialEvent when arduino sees a beat happen
  heart--;                    // heart is used to time how long the heart graphic swells when your
heart beats
  heart = max(heart,0);       // don't let the heart variable go into negative numbers
  if (heart > 0){             // if a beat happened recently,
    strokeWeight(8);          // make the heart big
  }
  smooth();   // draw the heart with two bezier curves
  bezier(width-100,50, width-20,-20, width,140, width-100,150);
  bezier(width-100,50, width-190,-20, width-200,140, width-100,150);
  strokeWeight(1);          // reset the strokeWeight for next time


// PRINT THE DATA AND VARIABLE VALUES
  fill(eggshell);                                      // get ready to print text
  text("Pulse Sensor Amped Visualizer 1.1",245,30);     // tell them what you are
  text("IBI " + IBI + "mS",600,585);                    // print the time between heartbeats in mS
  text(BPM + " BPM",600,200);                           // print the Beats Per Minute
  text("Pulse Window Scale " + nf(zoom,1,2), 150, 585); // show the current scale of Pulse
Window

//  DO THE SCROLLBAR THINGS
  scaleBar.update (mouseX, mouseY);
  scaleBar.display();
  } else {

  background(255);

  serialEvent2(myPort);

  // Draw the first plot
  plot1.beginDraw();
  plot1.drawBackground();
  plot1.drawBox();
  plot1.drawXAxis();
  plot1.drawYAxis();
  plot1.drawTitle();
  plot1.addPoint(xPos, humidity, "(" + str(xPos) + " , " + str(humidity) + ")");
  if (plot1.getPoints().getNPoints() > 50) {
    plot1.removePoint(0);
  }
  plot1.drawLines();
  plot1.drawLabels();
  plot1.endDraw();

  // Draw the second plot
  plot2.beginDraw();
  plot2.drawBackground();
  plot2.drawBox();
  plot2.drawXAxis();
  plot2.drawYAxis();
  plot2.drawTitle();
  plot2.addPoint(xPos, temperature, "(" + str(xPos) + " , " + str(humidity) + ")");
  if (plot2.getPoints().getNPoints() > 50) {
```

```
    plot2.removePoint(0);
  }
  plot2.drawLines();
  plot2.endDraw();

  // Draw the third plot
  plot3.beginDraw();
  plot3.drawBackground();
  plot3.drawBox();
  plot3.drawXAxis();
  plot3.drawYAxis();
  plot3.drawTitle();
  plot3.addPoint(xPos, acceleration, "(" + str(xPos) + " , " + str(acceleration) + ")");
  if (plot3.getPoints().getNPoints() > 50) {
    plot3.removePoint(0);
  }
  plot3.drawLines();
  plot3.endDraw();

  delay(200);
  xPos = xPos + 0.2;
  }
}

void serialEvent2 (Serial myPort) {
  // get the ASCII string:
  String inString = myPort.readStringUntil('|');

  if (inString != null) {
    //// trim off any whitespace:
    inString = trim(inString);
    float inputs[] = float(split(inString, ','));
    if (inputs.length == 4) {
    println(inputs[0], inputs[1], inputs[2]);
    }
   //now assign your values in processing
    if(inputs.length == 4){
     humidity = inputs[0];
     temperature = inputs[1];
     acceleration = inputs[2];
    } else if( inputs[0] == 'S') {
      timeForHeart = true;
      println(inputs);
    }
  }
}
```