IntelliGYM

ECE 445 Design Document

Justin Naal, Daniel Rymut, Srinija Kakumanu

jnaal2, drymut2, srinija2

Group 26

TA: Alex Sirakides

Spring 2021

Table of Contents

1 Introduction

1.1 Objective

It was estimated in November 2020 that 25% of health and fitness clubs would have closed due to Covid-19 [2]. “Fitness is a $34 billion industry, and an estimated 20% of Americans have a membership to some kind of fitness club, according to the International Health, Racquet & Sportsclub Association (IHRSA)” [1]. That means 20% of all Americans were forced to pivot to at-home workouts due to COVID-19. And “one of the [in-person] gym’s big appeals—besides easy access to equipment and workout space, two things that are expensive and may not be available at home—is access to both the expert knowledge of trainers and class instructors and the community knowledge and support of other people working out”[1].

So, while at-home workouts are an excellent way to stay healthy, displaced gym goers do not have access to trainers or spotters. This potentially leads to performing exercises poorly and over time, injury or strain. Additionally, working out at home means it is harder to stay consistent and motivated.

The way to address these problems is to give people a way to collect and examine data from their workouts. Our proposed solution is to build a smart exercise mat and companion mobile app to help at-home workouts. The mat would use pressure to analyze form while performing sets of exercise and the app would be used to build circuits of exercises and analyze performance data.

1.2 Background

We contend there is a strong need for a product such as ours because the number of people who had to pivot to at-home workouts skyrocketed due to COVID-19. But the need for IntelliGYM goes beyond use during quarantine. There is a huge portion of Americans who want to exercise but cannot afford trainers or gym memberships. Our product would address both displaced gym-goers and novice exercisers by giving them a standalone tool to improve their performance without high recurring cost.

IntelliGYM does not require users to have anything besides their smartphone. Users would only be performing bodyweight exercises. By creating an ecosystem where people can collect and study their data as well as build custom workouts, we are addressing the issue of ineffective and potentially strenuous exercises.

1.3 Physical Design

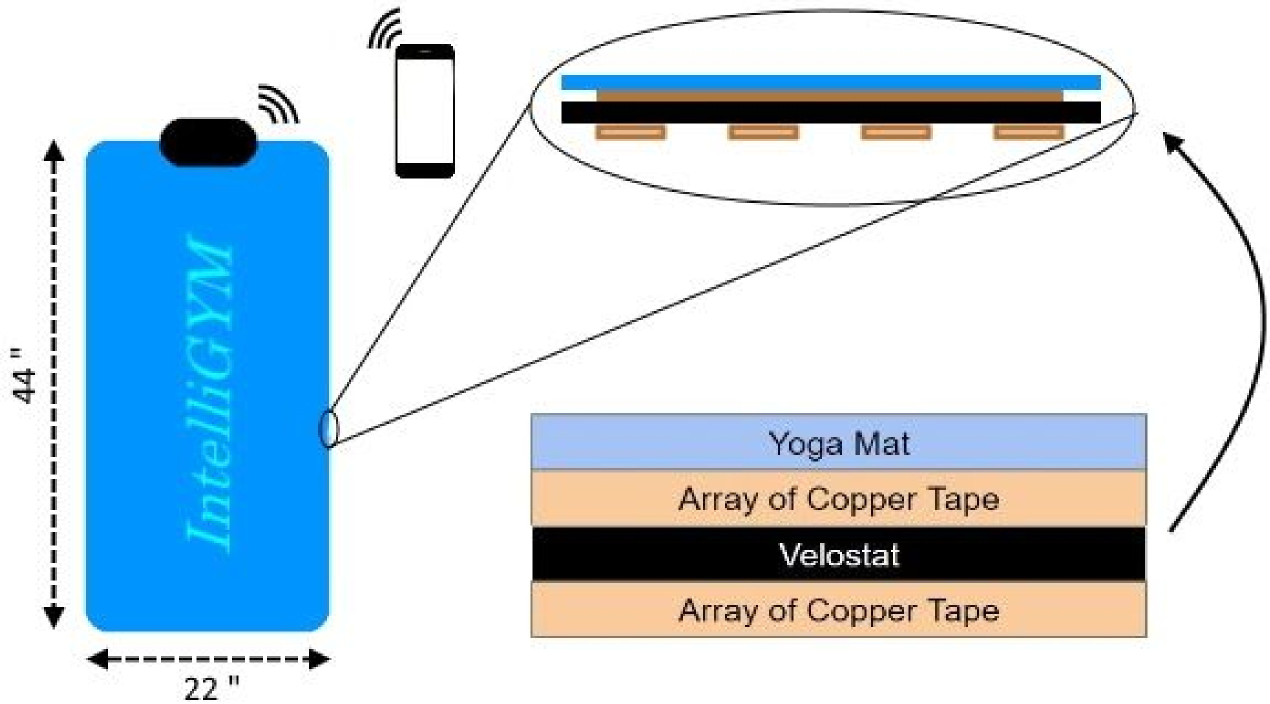


Figure 1: Top and Side View of IntelliGYM

1.4 High-Level Requirement

1. The mat is able to distinguish between the phases of the following exercises: Push-up [7], lunges [8], squat [5] [6], sit-ups [9], planks [7].
2. The mat is able to count reps of the aforementioned exercises within 90% accuracy.
3. The mat is able to differentiate between two different exercises (tell a push-up from a lunge) .
4. The mat is able to differentiate between two different qualities of exercises (a well-performed push-up and poorly-performed push-up.

2 Design

The IntelliGYM mat requires four modules shown in Figure 2 to operate successfully: a power supply module, a pressure sensing module, a control unit module, and a software module. The battery pack and voltage regulator in the power supply module ensure that the sensors on the mat as well as the microcontroller are continuously powered while turned on. They also ensure that both the 5V and 3.3V requirements of the components are met. The pressure sensing module consists of 3,872 sensors, each covering a ¼ square inch area of the mat. The control unit individually reads each of the pressure sensors and communicates them to the phone app through a bluetooth chip. Finally, the software app provides visual feedback and an interface for the user to personalize their experience.

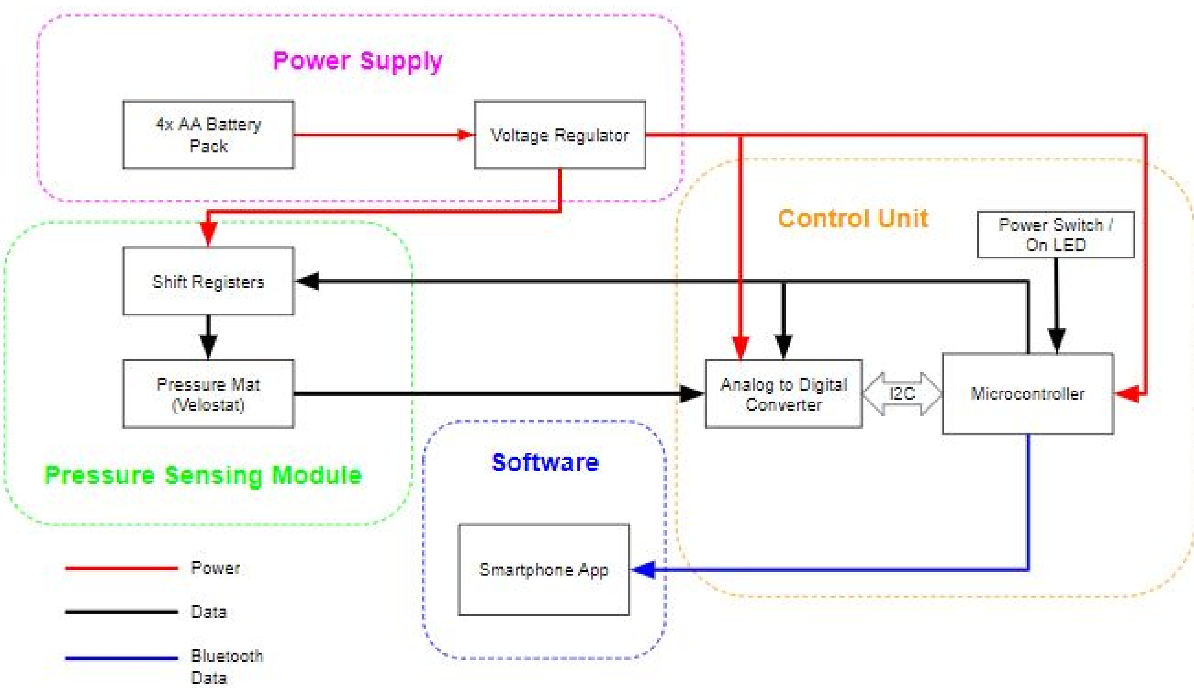


Figure 2: Block Diagram

2.1 Pressure Sensing Module

The pressure sensing module comprises the hardware that measures user input data. An array of copper cells separated by a piezoresistive material create varying current pulls, and these values
2.1.1 Pressure Mat (Velostat)

2.1.1 Pressure Mat (Velostat)

An array of pressure sensors is created through rows and columns of ¼ inch copper tape. The columns are separated from the rows by a thin layer of velostat, whose resistance values range from 800 Ω to 60 Ω between 0 and ~1000 grams. The shift registers are responsible for activating each column, and the analog signal is fed to the control unit through the ADC converter.

Requirement	***Verification***
1. Pressure mat is capable of differentiating ±10 gram changes in pressure. 2. At most, 50% of the pressure applied directly above one sensor should be registered by any neighboring sensor	1. a. Apply 5V to one column of copper tape and then add a 1kΩ grounded resistor to the end of one row of the tape b. Connect a voltage probe to the non-grounded side of the resistor c. Place 10g of weight where the 5V column and grounded row intersect. d. Observe voltage to ensure there is a change 2. a. Repeat the same setup as stated in 1a, but add 1kΩ grounded resistors to the row above and below the original b. Place a focused pressure on the central sensor intersection and record new voltage readings across the three resistors c. Compare the changes in voltage to ensure that 50% of the pressure was observed by the central sensor

2.1.2 Shift Registers

A system of 8-bit shift registers is serially connected to make an 88-bit circular shift register. Only one bit is high while the rest are low, and the high bit powers a column of the pressure mat array. The high bit indefinitely circles the register allowing continuous reads of the pressure mat array.

Requirements	***Verification***
1. The shift register supplies the column of copper tape with 5V ±2% and at least 5mA 2. Only one bit is active at any given time while operating at clock frequency of 500Hz	1. a. Connect V_{cc} of the shift register to 5V and read the voltage of each output pin when made high. b. Connect a 1kΩ resistor from the output to ground and ensure there is current flowing through with a ammeter

	connected in series. 2. a. Set first output pin high in shift register b. connect the serial in pin to the serial out pin and connect clock pin to a 500Hz square wave from the function generator c. Observe four consecutive output pins using the oscilloscope to verify that by the time one pin is high, the previous pin is low

2.2 Power Supply

Our power supply is planned for mobility and the mat does not need placement next to a power outlet.

2.2.1 4x AA Battery Pack

Using four 1.5V AA batteries which are connected in series, we can obtain a 6V output which will need to be regulated in order to power all other modules at the needed power levels.

Requirement	***Verification***
Securely holds 4 batteries and provides a constant 4.5-6.5 V DC output for 2 A-h	a. Connect the battery holder to an electronic load and draw 500 mA for 4 hours b. At the end of this time, measure the voltage of the battery pack and ensure it still supplies at least 4.5V

2.2.2 Voltage Regulator

The modules and components of the PCB will require either a 5V or 3.3V power supply, so we will need to step down the voltage to two different levels.

Requirement	***Verification***
1. Step down from 4.5-6.5V to 5V ± 4% at the output while providing at least 30 mA	1. a. Supply the regulator with 6.5V and connect it to a load that draws 30mA

2. Step down from 4.5-6.5V to 3V ± 4% at the output while providing at least 170 mA	b. Use an oscilloscope to make sure it is providing 5V with minimal ripple c. Repeat previous steps with a 4.5V supply 2. a. Repeat the same process as verification 1 above, but set the load to a constant 170 mA and verify an output of about 3.3V

2.3 Control Unit

The control unit module will be responsible for all control and clock signals being sent to the other modules. It will also need to send the data from the pressure mat to the phone.

2.3.1 Analog to Digital Converter (ADC)

The data that comes from the pressure mat will be an analog signal. In order to process this data it will be converted to a digital signal by the ADC. The most critical aspect of this module is that it is carrying out conversions with the fastest possible speed and the highest possible accuracy.

Requirement	***Verification***
Be able to process analog to digital conversions at a speed of at least 20k SPS	a. Supply power to the ADC, and set the analog max to 5V and the analog min to 2.5V b. Provide a 11k Hz (22k SPS) square wave with a 5V maximum and 2.5V minimum c. Verify that ADC outputs expected high and low digital values

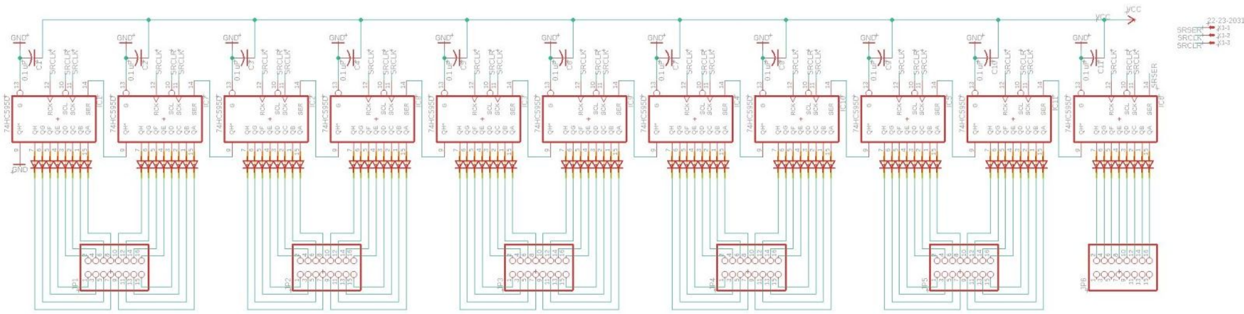
2.3.2 Microcontroller

The microcontroller will be responsible for sending out all control and clock signals to other components. It must also have the ability to read digital input data and communicate with the ADC using I2C protocol. Additionally, it will be responsible for transmitting data via bluetooth to the paired smartphone.

Requirement	***Verification***
1. Be able to communicate via I2C 2. Be able to wirelessly send data using bluetooth	1. a. Supply power to the microcontroller and ADC b. Use function generator to supply a sine wave to the analog input of the ADC c. Verify that the microcontroller can receive the digital output and communicate with the ADC using I2C protocol 2. a. Power the Microcontroller b. Upload a program that allows it to connect via bluetooth to an external device c. Verify that it shows up as a connectable device on smart phones that are close in proximity

2.4 Schematics

2.4.1 Shift Registers



2.5 Software

The smartphone app will be where the user can build circuits, look at their data and complete new workouts. The app will communicate with the mat using Bluetooth connection. We plan to use either the BeeWare or Kivy framework to develop the application.

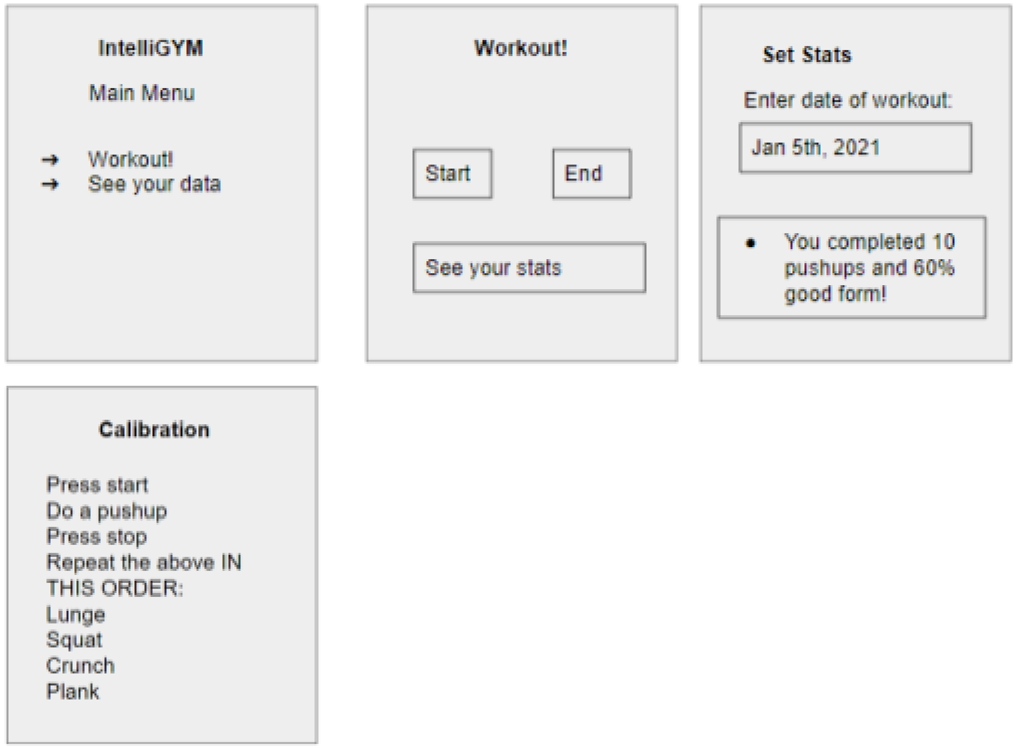


Figure 3: Wireframes for Mobile App Screens

2.5.1 Data Flow

Figure 4: Data flow for Workout Feature

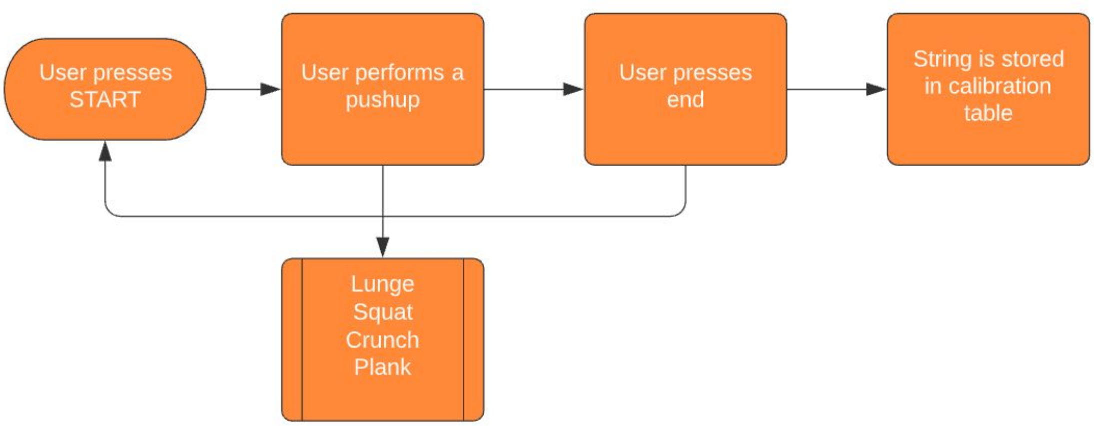


Figure 5: Data flow for Calibration Feature

Figure 6: Data flow for Feedback Feature

Our project states that a certain pressure pattern indicates the quality of a rep. We have sources to support this hypothesis linked in the High Requirements section.

2.5.2 Schema

Rep	
time	*TIME*
matrix	*PNG*
totalPressure	*Int*
exercise	*Int*
form	*Boolean*
date	DATE

Raw Data	
time	*TIME*
pressure	*Int[]*

Calibration	
exercise	*String*
matrix	*PNG*

Figure 7: Database Tables

2.6 Tolerance Analysis

One pivotal tolerance of our design is the Velostat's response to human weight. The design takes each reading of the sensor as a voltage divider between the Velostat's variable resistance and a 1kOhm fixed resistor. In order for our design to succeed, the resistance of the Velostat must be variable at and around the average weight of an adult, and the analog voltage reading must have the precision to distinguish the pressure from different phases of an exercise, i.e. the upward and downward movement of a push-up. Figure 8 below shows the pressure and resistance characteristics of Velostat:

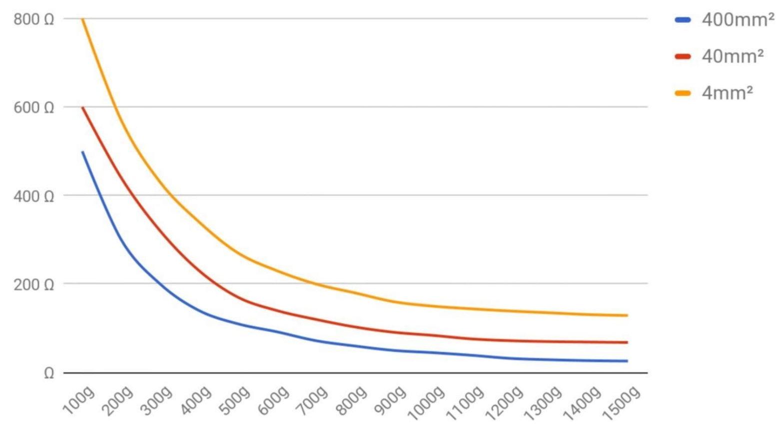


Figure 8: Velostat Characteristics

Figure 8 displays a dynamic range of 0 to 1000 grams. However, this range can be stretched by altering the effective area of the mat covered by the sensors. Since this design utilizes rows and columns of ¼" copper tape with ¼" of separation, the entire mat will not be covered by the sensors. The effective area percentage can be computed by

$$EA = \frac{sensor\ data}{unit\ area} \times 100\%\,, \qquad \text{Eq. 1}$$

where the sensor area is the copper tape intersection and the unit area includes the sensor area and its surrounding blank space. This gives an effective area of 25% and a theoretical range of 0 to 4000 grams. We will now compare these values to those of an average adult standing on their feet. If we take the average area of the sole of a foot as 27.4 square inches and the average body weight as 80.74 kg [4] , we can use Eq. 2 to determine the corresponding weight per sensor.

$$\frac{weight}{sensor} = W \times EA \div SA,\ W = average\ weight,\ EA = effective\ area,\ SA = surface\ area \qquad \text{Eq. 2}$$

The average weight per sensor for a standing position using Eq. 2 is 368 grams. This measurement fits well within the dynamic range of Velostat. Since we are using ¼" cross sections ($40.3\ mm^2$), 368 grams corresponds to roughly 200 Ohms, while exercises like crunches with greater surface area would yield greater resistances.

$$V = \frac{1000}{R_{Velostat}+1000} \times V_{in}\,,\ V_{in} = 5V \qquad \text{Eq. 3}$$

If the strenuous phase of an exercise pulled the pressure sensors to over 1000 grams, the resistance would dip to nearly 60 Ohms. Using the voltage divider rule shown in Eq. 3, the ADC would measure a difference in analog voltages of 0.55 V between the average and maximum pressure. If an exercise had a resting pressure lower than the average standing pressure found above, then the rate of change of the resistance relative to pressure would increase and an even larger voltage differential would be measured. Given an ADC with eight bits of precision and an analog input range of 2.5 V, the design could distinguish analog readings within 10 mV. This accuracy is over one order of magnitude less than the required differential to discern maximum and resting pressures and is sufficient for our design.

2.7 Risk Analysis

The exercise mat is the most significant risk to the successful completion of this project. There are not many available resources that provide information on using velostat as a pressure sensor. So we will need to run some preliminary tests to see how accurate and consistent the data will be. Properly implementing our proposed design of about 3,800 sensors in order to achieve a detailed pressure mapping will be met with many potential challenges along the way. The amount of power needed to obtain a reading is another unknown factor that may affect the design as a whole. Our hope is that this will be an accurate, efficient, and reliable method for producing a cost effective pressure mapping; however, we expect to have some challenges as we learn to use this material that has primarily been used as an electrically conductive packing material.

3 Safety and Ethics

The primary ethical concern of IntelliGYM is privacy. In order for this product to use the pressure data as effectively as possible, we will need to know the users size, weight, and height. For many people, especially those trying to get in shape, this may be sensitive information. Our users assume that the private data they enter is safe, so we must ensure that the data they put in their smartphone will not be used or distributed in any way that breaches privacy. To accomplish this, we guarantee that user data will not be stored on a server and that the app will not connect to the internet. This allows us to assure users that their data is secure as long as the phone itself is not broken into or compromised. In other words, we must ensure that we adhere to principle 1.6 of the ACM Code of Ethics, “Respect Privacy”.

Furthermore, the IntelliGYM mat must adhere to principle 1.2 of the ACM Code of Ethics, “Avoid Harm”. The mat contains conductive copper tape and is battery powered, so users should avoid water while using the IntelliGYM mat. Any contact between electrical components and water may cause the circuit to short and overheating to occur. Thus, users should not use our product outdoors or near any source of water. Users will unavoidably sweat during a workout, so the yoga mat material will be water resistant and fully encompass all electronic components such that none are exposed.

4 Costs

In order to estimate costs for this project, we begin by estimating labor costs of the three group members. If we assume an average pay of $30/hour and estimate that we each work about 10 hours/week, then the following equation shows an approximation of labor costs over the 16 week semester.

$$Labor\ Cost = 3 \times \frac{\$30}{hr} \times \frac{10\ hr}{week} \times 16\ weeks = \$14,400 \qquad \text{Eq. 4}$$

Part	**Manufacturer/PN**	**Price**
Copper tape (¼" x 21.9 yards) (x5)	Oubaka/OFC00006	$29.90
Microcontroller w/bluetooth Tx/Rx	STMicroelectronics/STM32WB55RGV6	$11.67
Velostat sheet (x8)	Adafruit Industries/1361	$39.60
Analog to Digital Converter	Maxim Integrated/ MAX1038AEE+T	$7.58
Assorted electrical components (connectors, diodes, resistors, etc.)	N/A	$15
Shift Registers (x11)	Texas Instruments 74HC595D	$4.16
Multiplexer (x7)	Texas Instruments CD74HCT4051(E/M)	$4.50
Total Parts Cost		**$112.41**

With our estimated costs for both labor and parts, we can make an assumption that the total development cost for the IntelliGYM product is about $14,513.

5 Schedule

Week	Justin and Danny	Sri
3/1	Make schematic to show pressure mat/ADC systems	Implement database
3/8	Order parts for/start construction on Velostat mat Collect data on resistive velostat properties	
3/15	Finish PCB design	Implement frontend
3/22	Finish construction of mat	
3/29	Solder PCB components	Implement calibration
4/5	Program/test/debug PCB	Send data via Bluetooth
4/12	Connect Mat to PCB and begin testing on system	Implement analysis algorithm
4/19	**Prototype Due**	
4/26	Work on finishing the Final paper	Work on finishing the Final paper
5/3	**Final Paper Due**	

References

[1] K. Eschner, “COVID-19 has changed how people exercise, but that doesn't mean gyms are going away,” *Fortune*, 12-Jun-2020. [Online]. Available: https://fortune.com/2020/06/11/coronavirus-gyms-workouts-fitness-apps-reopening/. [Accessed: 17-Feb-2021].

[2] “One in Four Health & Fitness Clubs Could Close by Year-End,” *IHRSA*. [Online]. Available: https://www.ihrsa.org/about/media-center/press-releases/15-of-health-fitness-clubs-in-the-u-s-permanently-closed/. [Accessed: 17-Feb-2021].

[3] S. Dufresne, “Hi-Res, Body-Sized Pressure Sensor Mat,” *Hackaday*, 29-Oct-2017. [Online]. Available: https://hackaday.com/2017/10/29/hi-res-body-sized-pressure-sensor-mat/. [Accessed: 17-Feb-2021].

[4] Strzalkowski, Nicholas & Peters, Ryan & Inglis, John & Bent, Leah. (2018). Cutaneous afferent innervation of the human foot sole: What can we learn from single unit recordings?. Journal of Neurophysiology. 120. 10.1152/jn.00848.2017.

[5] David Cruz, DC. “Squat Form – What Does It Tell Us? Part 1.” *NASM*, 2020, blog.nasm.org/newletter/squat-form.

[6] Koh, Da Hyun, et al. “Plantar Pressures in Individuals with Normal and Pronated Feet According to Static Squat Depths.” *Journal of Physical Therapy Science*, The Society of Physical Therapy Science, Sept. 2015, www.ncbi.nlm.nih.gov/pmc/articles/PMC4616105/.

[7] Chuckpaiwong, B, and T Harnroongroj. “Http://Www.smj.org.sg/Sites/Default/Files/5007/5007a6.Pdf.” Republic of Singapore, Singapore, 2009.

[8] Dorman, Deanna, and Deanna Dorman. “How to Do The Perfect Lunge.” *Paleo Blog*, 12 Jan. 2018, blog.paleohacks.com/how-to-do-the-perfect-lunge/#:~:text=How%20to%20Correct%20It%3A%20When,toes%20in%20the%20front%20foot.

[9] Finn, Christian. “Should I Do Sit-Ups?” *Men's Health*, Men's Health, 10 Dec. 2018, www.menshealth.com/uk/building-muscle/a750314/should-i-do-sit-ups/.