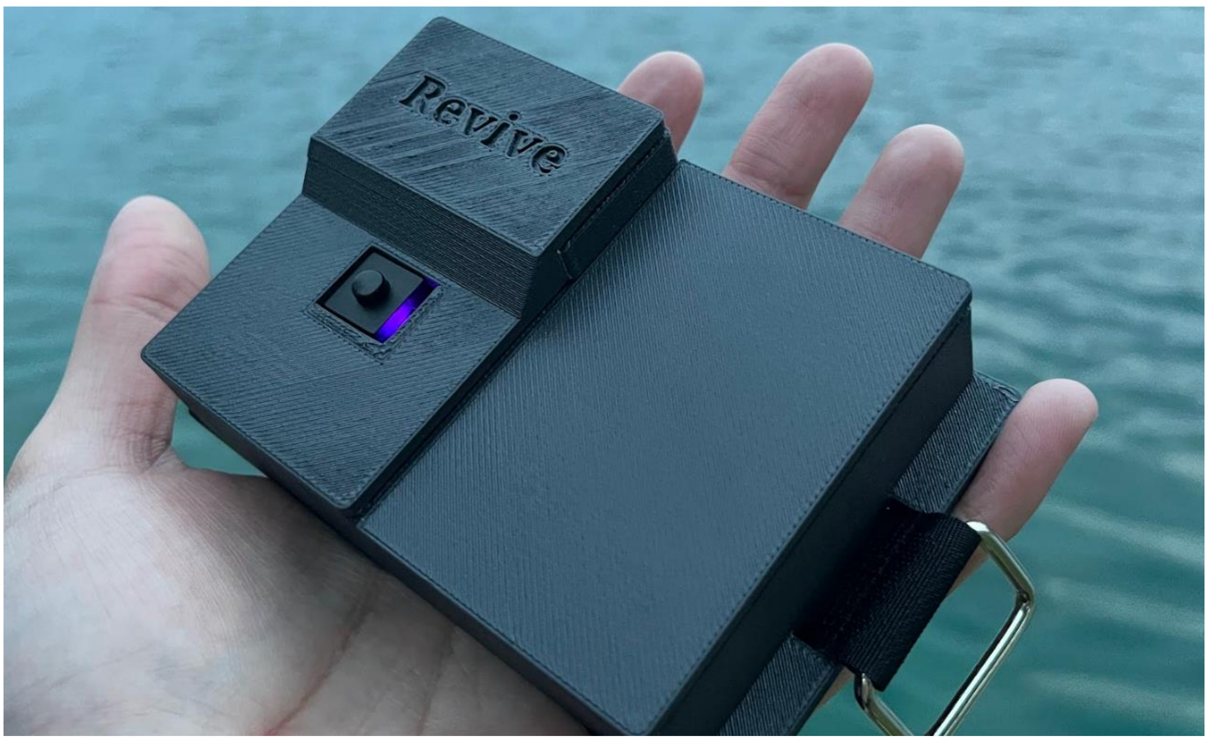
UNIVERSITY OF NEVADA LAS VEGAS
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

EE498 Senior Design
Spring 2023

Revive: A Sensor-Based Knee Rehabilitation Device

Final Project Report



Group Members:

Name (Print)	CPE/EE/ME
Edreese Basharyar	EE
Maxwell Stonham	EE

Instructor: Dr. Grzegorz Chmaj
Faculty advisor: Dr. Venkatesan Muthukumar

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Abstract

Osteoarthritis is a degenerative joint disease commonly diagnosed in the elderly population and is one of the main causes of disability; most people with severe knee arthritis must undergo total knee replacements, with the rehabilitation period ranging from several weeks to months. However, there is a major deficiency in portable equipment on the market that individuals can use to consistently track their progress during the rehabilitation process. Therefore, we have created a sensor-based knee rehabilitation device that is accessible and affordable for all individuals. Our device provides real-time feedback to patients, allowing them to understand how their knee is moving and how they can adjust their movements. This can help to improve their overall rehabilitation. The integration with a smartphone device allows for easy and convenient access to the rehabilitation program, making it more accessible for individuals. Additionally, our device can track progress over time, providing valuable information for both patients and healthcare providers. This can help to ensure that patients are making the most progress possible during their rehabilitation. One of the key benefits of our sensor-based knee rehabilitation device is its ability to provide personalized rehabilitation programs. By using sensors to track the movements of the knee, our device can create customized rehabilitation programs that are tailored to the specific needs of every individual. This can help to ensure that patients are able to make the most progress possible during their rehabilitation. Overall, our device is the most effective and affordable option on the market for individuals who have undergone total knee replacement surgery due to severe osteoarthritis. By providing real-time feedback, tracking progress, and creating personalized rehabilitation programs, our device can help individuals to achieve their rehabilitation goals as efficiently and effectively as possible.

Introduction & Background

Osteoarthritis is a very common disease for the elderly population and is a one of the main causes of disability; the most common form of osteoarthritis occurs in the knee. Therefore, most people with severe knee arthritis undergo total knee replacements, with the rehabilitation period ranging several weeks to months to get back to a fully mobile state. To speed up the recovery process, rehabilitation exercises are essential to restore the operations of the knee joint; however, there is a major deficiency of portable equipment that people can use to consistently measure and monitor their progress of recovery.

Our goal is to design a device that is affordable, easy to use and access, and allows users to monitor the information provided in a simple and consistent way. The communication between the doctors and the users will be clear and more direct, as it significantly reduces the difficulty and time of receiving information through traditional in-person rehabilitation programs. With this device, the information also allows doctors and users to predict the duration of the rehabilitation period, as well as knowing how to prevent heading in the wrong direction of recovery.

There are three devices that perform similar functions to our project topic: “Quell”, a wearable knee device that uses transcutaneous electrical nerve stimulation integrated with a smartphone app in order to relieve knee pain, “TracPatch”, a wearable sensor-based knee device that measure range of motion, steps taken, and wound temperature that uploads data in real-time with a smartphone app, and “KIMIA”, a wearable sensor-based knee device that shares the data of the patients’ exercise sessions and daily living activities directly to therapists in real-time to create custom prescriptions.

Our device will focus specifically on convenience and accuracy during the physical therapy process. The normal and widely used solution to treating patients in need of rehabilitation would be either at-home remedies or physically go to a therapy center. Our product would be considered an at-home remedy, but it differs from normal at-home remedies because of the electrical aspect of our device. Normal at-home remedies are usually by instructions that a physical therapist would give to a patient for joint exercises during the healing process, whereas our solution would be to electronically assist patients with these same exercises to ensure that the exercises being done at home are being done correctly. The purpose of this would be to allow proper exercise routines to take place to prevent injuries in case the patients misunderstand the remedies given from a physical therapist, as well as to optimize the exercises being done by patients by monitoring exactly what they need to do through an electronic device and without the use of a physical therapist. This can be much more convenient for people who may have transportation issues, no insurance or to those who wish to stay home when completing the healing process and gives an extra option for those who prefer using an electronic device for accuracy and convenience.

The project makes use of a PCB that is designed to include multiple sensors to track and monitor progress on physical therapy for patients in need of muscle rehabilitation due to injuries related to the knee (or other joints) as well as other hereditary diseases. The PCB will also implement a module that wirelessly connects itself to a smartphone for ease of use when monitoring progress. To build a PCB for the sensors, the circuit layout will be designed with the use of computer-aided design software (CAD). The design would specify the placement and connections of all the electronic components such as the sensors and will be enclosed with the design of a case that will be 3D printed. This case will be designed to cover all of the parts that we will use for this device, including the PCB. The case will then be attached with Velcro straps to securely attach the device to the knee, allowing it to provide support and resistance during the rehabilitation exercises. These straps can also be adjusted to fit different sizes of knees and can be easily removed or attached as needed. This allows our device to become more versatile, easy-to-use, and effective at helping people recover from total knee replacement surgery and other standard knee injuries.

Current Market Solutions

	Vendor	Consumer	Popularity	Ease-of-Use	Monitoring Activities	Price	Comment
Quell	Neuro Metrix	Can be used for anyone with general joint pain.	Very popular since its features include a long-lasting rechargeable battery, future updates will have no additional cost.	Very easy, since it is comfortable to wear, works automatically, and easy to calibrate.	Uses smartphone app to measure step count, time walking, customizes therapy sessions, and has weather alerts.	$249	This product has similar characteristics to the use of a wearable device for joints with a smartphone app, but it does not measure the progress of the functions of the knee, and it does not provide rehabilitation exercises or gyroscope measurements. It directly relieves any joint with electrode stimulations and can be used for anyone who suffers from mild to severe pain; it does not particularly focus the needs of improving the recovery of patients with severe knee arthritis.
Trac Patch	TracPatch Health	Used to regain functional range of motion after surgery for patients recovering from Total Knee Arthroplasty. It can be used for similar knee therapy uses.	Very niche, as it is not available to the public and can only be consulted by contacting them through email.	Easy to use and utilizes Bluetooth to pair with a smartphone app. Uses an adhesive disposable patch to connect to the upper and lower parts of the legs.	Uses smartphone app to measure range of motion progress, exercise compliance, pain, and physical therapy. Transfers data to the TracPatch cloud for real time viewing on app and web dashboard	N/A	Although this product does have similar characteristics in terms of measuring the range of motion and monitoring activities, it is very hard to purchase for consumers. The company is not as popular and is hard to contact, but it has similar features and innovations that we want to implement for our own device. Although this is an excellent product, the only thing that it suffers from is its accessibility.
Revive	Edreese and Maxwell	Can be used for anyone with general joint pain in the knee. Main purpose for those recovering from surgery. It can be expanded to other joints in the future.	N/A	Easy to use. Has Velcro straps to attach the device onto the knee.	Uses app to monitor real-time activities. Stores data of training for feedback. Monitors angles, counts reps and has training using timers. Vibration motors are used to get the attention of the individual whenever the initial and final position of the exercise is reached.	$70	We are putting a sole focus on optimizing the rehabilitation period of the patients after undergoing total knee replacement. We made it as convenient and intuitive to use for the user as possible, allow information to be sent directly to the doctors in order to help minimize any problems and customize the patients' sessions remotely. It will be much more affordable compared to similar devices.

Table 1. Comparison of available devices

	Accessibility	Price	Strengths	Weaknesses
Quell	High	Very High	- High resolution - Long battery life	- High price - Not meant for joint training
Trac Patch	Low	N/A	- Long battery life - Good features - Easy to use - Implements app - Real-time monitoring and feedback	- Difficult to purchase
Revive	High	Medium	- Good features - Affordable Price - Implements app - Real-time monitoring and feedback	- Uses AA batteries (not rechargeable) - Real time angle monitoring is dependent on Wi-Fi strength (instead of potentially using Bluetooth for a local connection).

Table 2. Strengths and weaknesses of available devices

Research Results

At first, we were planning on creating our device with the ATmega328PB microcontroller and the ESP-8266 Wi-Fi module. However, as we continued to do more research, we realized that these components are outdated, and more expensive than the newer models that have come out recently. Therefore, we decided to change the microcontroller to the ESP-32. The ESP32 and the ATmega328PB are both microcontrollers, but they are designed for different purposes and have different capabilities. The ESP32 is a newer and more powerful microcontroller than the ATmega328PB, and it is better suited for tasks that require a lot of processing power, such as working with Wi-Fi or Bluetooth.

The ESP32 also has more built-in peripherals, such as touch sensors and temperature sensors, which makes it easier to use in a wide range of applications. With this microcontroller, the ESP-8266 was not necessary since the Wi-Fi module is already built into the ESP-32 microcontroller itself. However, as we continued to do more research, we have found an item that includes most of the features we would have had to buy externally; what we found is denoted as the M5Stack Core2 Esp32 IoT Development KIT, which is incorporated with the use of AWS IoT software. It is a complete solution for developing IoT applications. It includes the ESP32 microcontroller, and a variety of sensors and components, including the gyro, vibration motor, and the accelerometer sensors that we wanted. The kit is designed to be easy to use, even for people who are new to microcontrollers and IoT development. It is fully compatible with the Amazon Web Services (AWS) IoT platform, so we can connect our IoT applications to the cloud that the AWS platform provides. The ESP32 microcontroller in this kit has built-in support for Wi-Fi and Bluetooth, which is a main feature we wanted to incorporate for this project. The kit includes a lot of other sensors, such as a temperature sensor, a humidity sensor, and a light sensor that we can use if needed. The kit includes all the software you need to get started, including the Arduino Integrated Development Environment (IDE) and a lot of other libraries that are very helpful in the IoT field. Therefore, this research has improved the quantity of parts that we will be using since this kit has all the features that we wanted to implement into one compact device.

The M5 Development Kit was used as our rough prototype for the early stages of our development. We decided to end up using Google's Firebase instead of Amazon's AWS service due to Firebase's ease of use, which helped us tremendously given the time constraints that we had to adhere to. Using Firebase allowed us to finish our project in time and gave us the tools needed to make a simple and intuitive smartphone app that was integrated with our device for users to control with. Alongside Firebase, we used Flutter which is an open-source software development kit that is also made by Google and is used to easily develop smartphone apps. The app that we made is considered a Flutter app and it is written in the Dart programming language. To work with our ESP32 and integrate that with our app, we decided to use Arduino code for the ESP32 side of things (with the MPU6050) to gather the angle data and send that data through to the Flutter app on VSCode. Flutter is also generally chosen over AWS since it is a much simpler method of developing an app but has less flexibility in terms of its features. However, since our project isn't purely app-based and doesn't require heavy app usage, we decided to learn to use Flutter instead to save time since it had enough capabilities to implement what we needed.

In terms of the physical components of the device, we had to fabricate a PCB to work with the ESP32, as well as a 3D case that all the electronics would fit into. For the PCB, the software we decided to use was KiCad, which is a common CAD software that allows us to design a schematic with all the parts we decided to use and connect them to each component used for the device. After the schematic was made, we viewed it through the PCB viewer and from there designed the PCB to be the appropriate dimensions needed to fit onto the ESP32 to act as headers to facilitate for the positioning and security of our vibration motors, MPU6050, and on/off button. The PCB files are then obtained from KiCad and sent online to be fabricated and shipped. We decided to use PCBWay as our manufacturer because it was one that we were familiar with and allowed for multiple customizations to the PCB, the only customization we used being the color change from the standard green color to black instead.

The 3D case itself was made using a simple online tool called TinkerCad. Initially, we were considering the use of SolidWorks to design the case, but since we didn't have any parts that were too complex (hinges, cylinders, moving parts, etc.), we decided to use a much simpler alternative to save time and reduce the need for learning a totally new software that we were unfamiliar with. This saved us a lot of time since our 3D model was a fairly simple shape and didn't require any intricate design specifications.

Specifications of the project

Functionality & conceptual design:

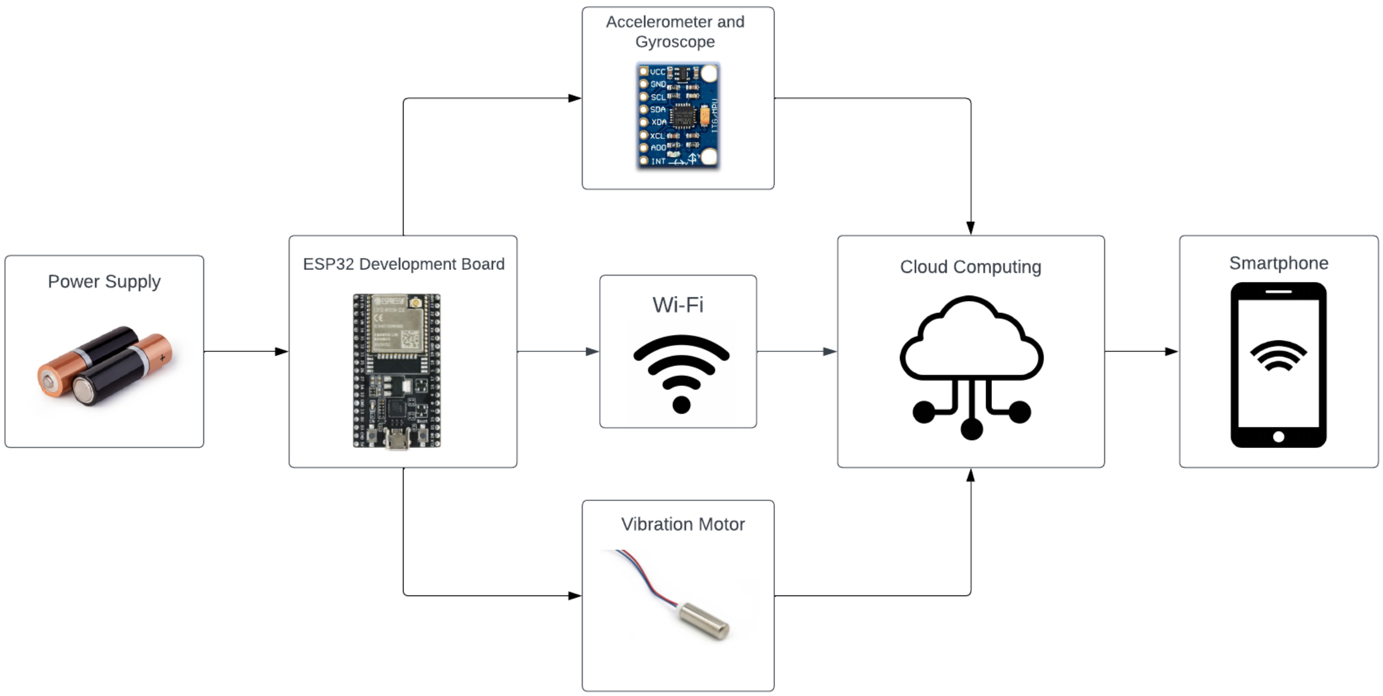


Figure 1. Block Diagram

Use Cases:

The device will be given to the patient after their first physical therapy session. The physical therapist (PT) will then help the patient in working the device and calibrating it to properly teach the patient how to work the device so that they will be able to use it remotely at home. Once taken home, the patient will attach the device onto the knee using a Velcro strap and press the button to turn the device on. The patient will then link the device to their smartphone using an app and will then choose the exercise that they are trying to do through their smartphone. This is when they will be prompted to calibrate the device to determine the patient's "original" position so that the device can determine how far up or down the patient will need to tilt their knee for a particular exercise. The two options that they could do for the exercises would be the repetition counter and/or the timer. For example, if the patient chooses to do squats, the device will be calibrated to the patient's reset position and once the patient starts the exercise, the device will alert the patient if they are squatting too low or not. It will also count how many times a patient has squatted as well as a timer to indicate how long each set is going to last. Once completed, this data will be recorded onto the smartphone to track the patient and their progress. The PT’s will also have access to this information and can give feedback on how quickly the patient is progressing with each exercise.

Architecture & Design

KiCad Schematics and PCB Design:

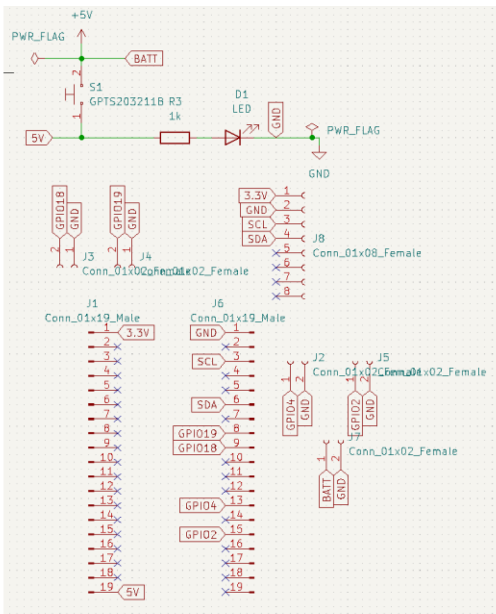


Figure 2. Schematic

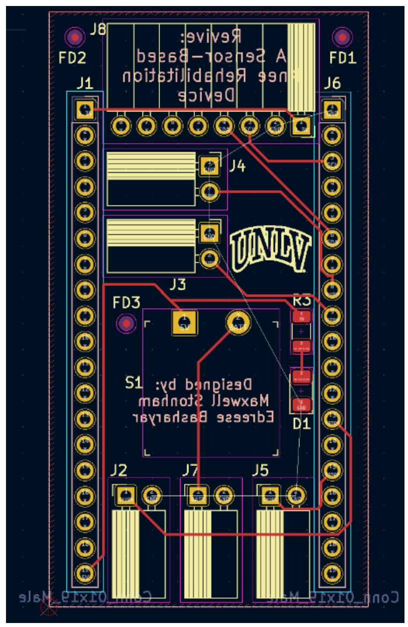


Figure 3. PCB (without ground plane)

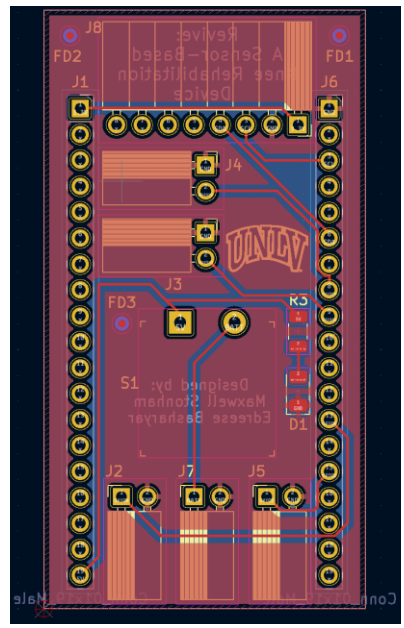


Figure 4. PCB (with ground plane)

The above pictures show us the schematic used for our project and the PCB design we finalized with. The PCB acts as a shield to the ESP32 DevKit with standard 2.54mm male headers soldered onto the sides of the PCB to attach onto the ESP32. The PCB is also measured to fit onto the ESP32 with no issues in terms of the width. The specific pins used on the ESP32 are shown below:

Pin Number	Use
5V	Turns on the ESP32
3.3V	3.3V Output for powering the MPU6050
GND	Ground
GPIO 22	SCL to connect to the MPU6050
GPIO 21	SDA to connect to the MPU6050
GPIO 2	3.3V applied to the vibration motor when requirement is met
GPIO 4	3.3V applied to the vibration motor when requirement is met
GPIO 18	3.3V applied to the vibration motor when requirement is met
GPIO 19	3.3V applied to the vibration motor when requirement is met

A button is also used to toggle the on/off switch to power the device from x3 AA batteries connected to the 5V pin on the PCB. The vibration motors are plugged into the device using simple 22 AWG wires that plug into the female headers and fitted to the left and right of the ESP32 module. The button is also connected to an SMD resistor and LED to notify users when the device is on or off.

3D Case Design:

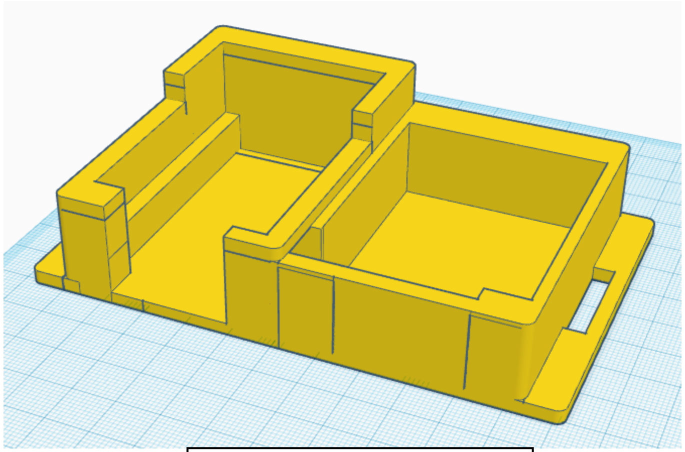


Figure 5. 3D Case (Body)

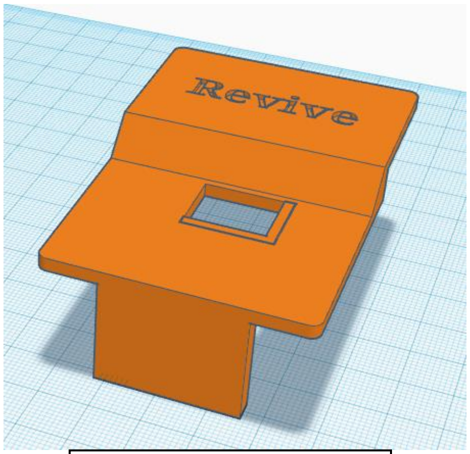


Figure 6. 3D Case (Lid)

The 3D case design is made through TinkerCad, which is a simple online tool to create 3D models. The design specifications mainly consisted of tucking in the vibration motors in an equal space to that the device fits in the case tightly without much rattling. These measurements were taken and implemented onto TinkerCad and was successfully printed with no unnecessary gaps to reduce rattling as much as possible. The vibration motors are placed onto a space to the left and right of the ESP32 (shown on the top left image in yellow) and are wired appropriately to ensure a secure connection. Once everything was wired up, we added a lid onto our case (top right picture in orange) with a hole big enough for the button to poke out of so that users can easily access it. The wiring from the battery case to the ESP32 needed to be soldered onto the PCB instead of female headers because of the vibration. We tried adding female headers to simply plug the battery pack into the 5V input to the ESP32, but encountered an issue regarding keeping a stable 5V connection since the vibration was so strong that it would disconnect the 5V wire input from the 5V female header. This issue was resolved by simply wiring the battery pack onto the PCB directly to ensure a stable connection.

Simulation

Android Emulator:

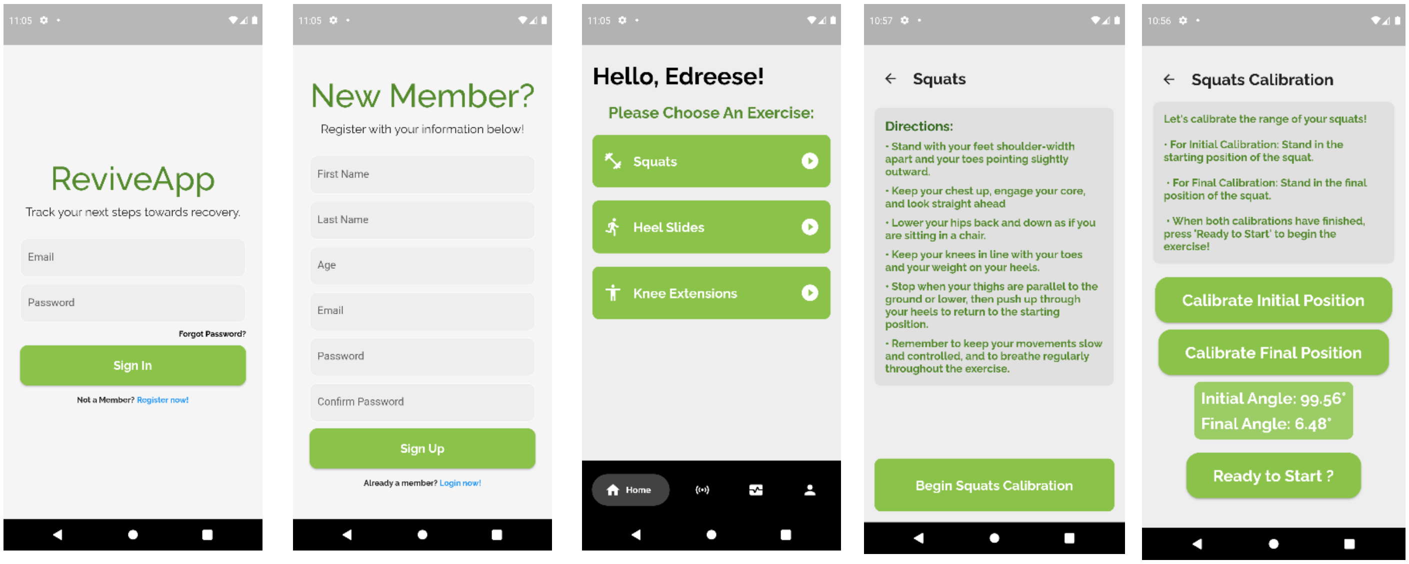


Figure 7. (Left to Right) Login Page, Create an Account, Home Page, Squats Instructions, Squats Calibration

Most of the simulations were done through VSCode and an android emulator. Through the Flutter app on VSCode, the device can be chosen to run the code for the app. This device can be a device chosen from the Android emulator externally. So, when the code is running with an android device chosen, we simulated how the app would run as if it was installed on an actual android. Shown above in Figure 7 is how the app looks on an android emulator. We also tested this app on an actual android and installed the .apk file to confirm that it does run well on an actual smartphone.

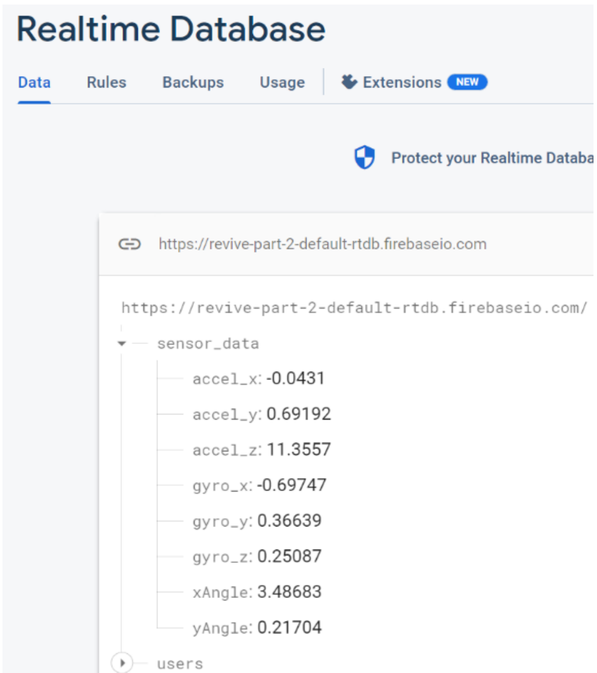


Figure 8. Sensor data on Firebase

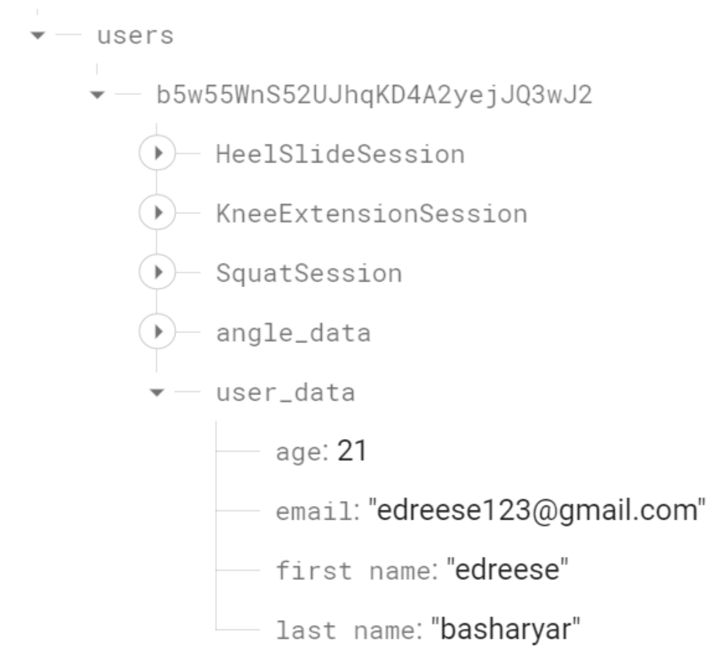


Figure 9. User data on Firebase

Figure 10. Calibrated angle and squat counter data on Firebase

Figure 8 shows the raw sensor data taken from the MPU and stored onto Firebase's Realtime Database. When the device is turned on, these sensor values are updated in real time depending on which user is chosen.

Figure 9 shows the user data. Each time a new user creates an account, a new UID (User ID) is created where angle data can be stored into this unique branch.

Figure 10 shows the different exercises as well as the dates and times that each exercise was done alongside the calibrated angle values and counters to track how many times they succeeded the exercise and how high or low they went in terms of their leg's angles.

Test Plan

	Inputs / actions to the device	Predicted Completion	Actual Completion
Test case #1	Test sensors and display angle	Winter break	Winter Break
Test case #2	ESP32 Code (Final)	Winter break	April 2023
Test case #3	Calibration Code	Winter break	April 2023
Test case #4	App development	Winter break	May 2023
Test case #5	PCB Design on KiCAD	Jan-Feb 2023	April 2023
Test case #6	PCB Sent for fabrication	March 2023	April 2023
Test case #7	3D Model on TinkerCad	Feb-March 2023	April 2023
Test case #8	Fabricate and finish final design	March-May 2023	May 2023

Table 3. Test plan

Current form of the project

Figure 11. Final Design (closed)

Figure 12 & 13. Final Design (opened)

The finished project is shown in the pictures above. The top left picture shows the assembled project with the lids shut closed. There are two sections to the device, the left section comprising of the ESP32, custom PCB, vibration motors, and MPU6050. The right section comprises of the battery case with x3 AA batteries included. The battery case is soldered onto the PCB that is connected to the ESP32 to power all the electronics. The 3D case is modeled specifically to fit a lid that allows an easy open-close mechanism without the need for hinges or screws. This also keeps the device looking cleaner. On the bottom of the device is the Velcro strap that is used to attach the device onto the patient's leg.

Roles & skills in the project

	Objects involved	Required skills
Smartphone App Designer	Flutter and Firebase	- Knowledge of UI design principle - Prototyping and testing functions - Knowledge of understanding dart programming language
Microcontroller Programmer	ESP32 Microcontroller	- Knowledge of ESP32 microcontroller functionalities - Knowledge of Arduino IDE programming
Case Designer	Device Case	- Knowledge of 3D modelling software such as TinkerCad/Solidworks - Understanding the optimal dimensions and sizing for the design - Understanding the functionality and appeal of the design of the case
PCB Designer	PCB	- Knowledge of KiCAD/Diptrace Programs - Designing schematics and 3D models of printed circuit board

Table 4. Roles & skills

List all the roles mentioned in Table 3 and assign names of team member to each role:

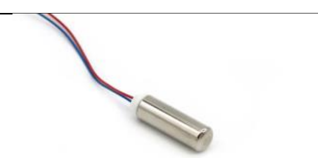
	Assignment
Software Related Components	Edreese Basharyar
Hardware Related Components	Maxwell Stonham

Table 5. Roles assignment

ITEM	Name
Back-end and Front-end App Development	Edreese Basharyar
Secure User Authentication and Cloud Database Storage Security	Edreese Basharyar
ESP32 Code and Cloud Integration with App	Edreese Basharyar
PCB Design and Testing	Maxwell Stonham
PCB Soldering and Parts Purchase	Maxwell Stonham
3D Model Design and Print	Maxwell Stonham
EE497 Slides Presentation	Edreese Basharyar and Maxwell Stonham
EE497 and EE498 Videos	Edreese Basharyar and Maxwell Stonham
EE497 Final Report	Edreese Basharyar and Maxwell Stonham
EE498 Poster	Edreese Basharyar and Maxwell Stonham
EE498 Final Report	Edreese Basharyar and Maxwell Stonham

Table 6. Items done

Parts List

	Parameters	Picture	Att. id
ESP32-DevKitC V4	240MHz dual core, 600 DMIPS, 520KB SRAM, Wi-Fi, GPIO Pins		https://www.mouser.com/datasheet/2/891/Espressif_Systems_01292021_esp32-1991551.pdf
MPU6050	3-Axis gyroscope with programmable FSR of ±250 dps, ±500 dps, ±1000 dps, and ±2000 dps 3-Axis accelerometer with programmable FSR of ±2g, ±4g, ±8g, and ±16g		https://product.tdk.com/system/files/dam/doc/product/sensor/mortion-inertial/imu/data_sheet/mpu-6000-datasheet1.pdf
Vibration Motor	1.5-3V, 8000-16000RPM Vibration Strength		https://www.amazon.com/tatoko-vibration-Waterproof-8000-16000RPM-toothbrush/dp/B07KYLZC1S/ref=sr_1_7?crid=V7P2QTA974DN&keywords=vibration+motor&qid=1683863230&sprefix=vibration+motor%2Caps%2C153&sr=8-7

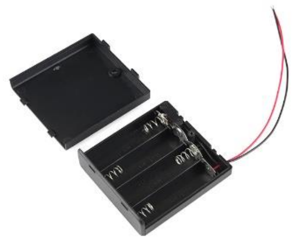
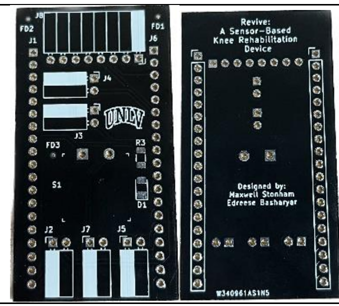
Battery Case	Holds x3 AA Batteries		https://www.amazon.com/Pack-Battery-Holder-Bundle-QTEATAK/dp/B07WY3VMNN/ref=sr_1_4?crid=T1DXD6UAHYVD&keywords=battery+holder&qid=1683864601&sprefix=battery+holde%2Caps%2C140&sr=8-4
PCB Shield	Wires up the ESP32 GPIO pins needed to connect to the vibration motors and power the device with female headers built soldered on for the connection		N/A

Table 7. List of required parts

Engineering standards used in the project

The following engineering standards have been used for the project:

Number (reference)	Symbol	Description	Justification why this standard has been used
1	IEEE 802.11g	54 Mbit/s, 2.4 GHz standard	This standard satisfies the requirements of our project, while maintaining the simplicity. Also there are many universal modules available on the market.

Table 8. List of engineering standards

Engineering constraints for the project

The following engineering constraints have been used for the project:

#	Name	Description	Specification of the constraint
1	Manual Wi-Fi connection from the ESP32	The Wi-Fi needs to be preset in the ESP32 code and determined beforehand (cannot be adjusted after code is uploaded onto the ESP32 board).	ESP32 Microcontroller
2	Connection strength	The angle updates in real time, but every now and then there would be a slight delay depending on the Wi-Fi signal.	ESP32 Microcontroller and Wi-Fi
3	Vibration Noise	The noise the vibration motor produces is very loud. This is due to the lack of padding that separates the motors from the inner walls of the case. This can be easily fixed if the inside of the case was made bigger to fit a thin piece of padding on the inner walls, but due to time constraints, we did not make this fix.	Vibration motor and device case

Table 9. List of engineering constraints

User's Manual

1. Turn the device on and connect it to Wi-Fi through the app.
2. Choose which exercise you want to work on.
3. Attach the device onto the part of the leg needed to be trained as per the instructions on the app.
4. Follow the instructions on the app and exercise as needed!

Final Remarks

In terms of future improvements, there are a few things that we could think about implementing such as:

- A slimmer design using rechargeable Lithium-Ion batteries instead of AA batteries.
- A potentially more comfortable alternative to Velcro straps such as stretchy bands that might be more fitting for all leg sizes.
- Safety features may be implemented, such as a heartbeat sensor to monitor a patient's BPM in case they are exerting too much stress when exercising, and an SOS feature to call medical services in case of an emergency.
- Improvements with the connection strength, such as using Bluetooth for the more local connection between the device and your smartphone and then using Wi-Fi to send to the cloud (as opposed to only using Wi-Fi for the connection between the device and the smartphone since this prevents users from using the device offline).

In conclusion, we have designed a device that has worked almost exactly as expected with all the necessary features that we proposed months ago. Revive offers an inexpensive solution to remote physical therapy. We offer a device that can be used for patients undergoing recovery after knee surgery and provide an at-home alternative to consumers who prefer to commute less or are lacking the options to regularly visit a physical therapy center. This device is also cost-efficient and uses cheap components that can be easily purchased and manufactured for commercial use. Having experienced COVID-19 and stay-at-home protocols, this device also offers a solution to an event like that, should something that extreme ever happen again.