ExoWear Medical Fitness Device

Final Report

Mengda Qi, Titus Fong, Caleb Klaus

TA: James Norton

ECE 445 Senior Design

Spring 2016

Abstract

We designed and created a medical fitness device that tracks medical exercises, provides real-time feedback and analytics, and seeks to improve patient compliance. A patient straps the device to his leg before a home physical therapy session and pairs it with his computer. While the exercise is being performed, the device's sensors capture acceleration and rotation data from the user's movements which is then modeled for visualization on a computer screen. An animated bar on the screen simultaneously displays the correct motion for an exercise chosen by the user that provides guidance and helps the user perform the exercise correctly. The device is powered by an embedded rechargeable battery and can be charged with a standard mini USB cable. This project received 3rd place in the 2016 Cozad New Venture Competition and has been accepted into the 2016-2017 iVenture, Polsky, and Summer@CIE Accelerators for further development.

Table of Contents

1. Introduction
    i. Motivation p3
    ii. Objectives p3
    iii. Benefits p4
    iv. Functions & Features p4
2. Design
    i. Overview p5
    ii. Control Subsystem p6
        (1) Microcontroller p6
        (2) Wireless Communication p7
    iii. Sensors Subsystem p8
        (1) IMU sensor p8
    iv. Power Subsystem p8
        (1) Charging Circuit p11
        (2) Power Switching Circuit p11
        (3) Buck Converter p12
        (4) Undervoltage Lockout p12
    v. Microcontroller Software p12
    vi. 3D Modeling Software p15
3. Design Verification
    i. Overview p15
    ii. Inertial Measurement Unit p15
4. Cost
    i. Labor: p16
    ii. Parts List: p16
5. Conclusions
    i. Accomplishments p17
    ii. Uncertainties p18
    iii. Ethical Considerations p18
    iv. Future Work p19
References p20
Appendix A: Additional Figures p21
Appendix B: Requirements and Verification p25

1. Introduction

i. Motivation

There is currently a shortage of 30,000 physical therapist and a projected continual undersupply of physical therapist for at least another 4 years [1]. There are over 13.6 million Americans with shoulder pain [2] (2003) and 52.5 million Americans with arthritis [3] (2012). With the Affordable Care Act, the "essential health benefits" now extend to preventative and wellness services, chronic disease management, and rehabilitative and habilitative services and devices - including physical therapy. That is why there is more outpatient physical therapy than ever before. Barriers to physical therapy treatment adherence can stem from multiple sources like, low physical activity levels, low self-efficacy, barriers to exercise, and low social support [4]. We have identified the following 2 sub problems that result from the barriers mentioned above. First, the end user (patients) find it difficult to remember how to perform their medical exercises correctly and as a result, neglect to do them on a regular basis. Secondly, patients lack the motivation to perform their medical exercises [5]. (Patient compliance can be as low as 30%) [6] Additionally, currently there is no way for physicians or physical therapist to monitor their patient's physical therapy progress at home without actually being there. Medicare home health rates for 2014 is $132.40 per physical therapist visit [7].

ii. Objectives

We recognize that the shortage of physicians can be solved in one of two ways. Either increase the number of physicians, or increase the amount of work each physician can do. We will focus on the latter option. By providing better technology, the amount of time needed on each patient should decrease, thereby increasing the amount of patients each physician can help. Physical therapy for knee rehab consists of a set of exercises. Here we concentrate on the development of a prototype system to help users do 2 of these exercises, straight leg raise and leg extensions [8]. The reason for this is because the first 3 months out of a 9 month rehabilitation plan includes the strengthening exercises mentioned above [9].

Patients often have to perform over six different types of exercise at different intervals throughout the day. This can easily overwhelm patients who already have a full day of work and as a result patients find themselves not practicing their exercises at all. We are lowering the barriers for patients by showing a simulation of the correct exercise while the patient performs the exercise. For our project this will be a basic simulation of the straight leg raise and leg extension, which the user will attempt to follow. The smartphone or PC will be next to the patient while they perform their exercises so they can easily view the simulation and their own motion on the screen and adjust their motion if they are falling behind or going too fast.

iii. Benefits

- Patient motivated to do exercises
- Convenience - Non-intrusive, lightweight device that can be easily strapped on
- Real-time motion displayed on PC with training motion to guide user during exercise
- Physical therapist can analyze results for a better holistic understanding of patient's rehab

iv. Functions & Features

- Real time motion tracking by IMU sensors
- On board intermediate data processing
- Bluetooth module which enables wireless data transfer between device and PC
- Microcontroller which handles communication between sensors and bluetooth module
- PC app which receives and models the data
- Re-chargeable battery and power circuit

2. Design

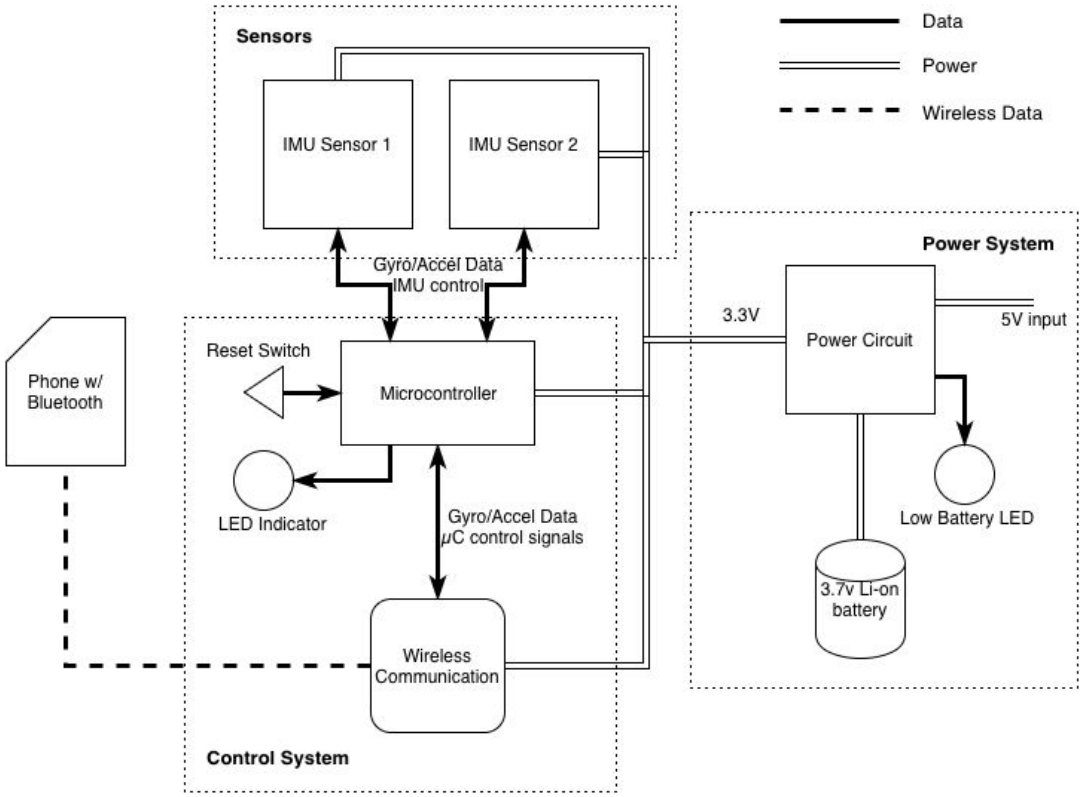


Figure 1. System Overview

i. Overview

Our overall system design is shown in figure 1. This project consists of three device subsystems, Control, Sensor, and Power, and two software modules Microcontroller Software, and 3D Modeling Software. The physical device (figure 6) was designed on a single PCB (figure 10) with breakout boards for the sensor subsystem. It will strap onto the user's leg with velcro straps, with one sensor above the knee, and one at the ankle. An illustration of the user performing a knee exercise with the device strapped on is shown in figure 8.

ii. Control Subsystem

The control subsystem (figure 2) manages the wireless communication between the mobile device and the microcontroller. It consists of a microcontroller, a bluetooth low energy module, a status LED, and a push button for powering and resetting the device.

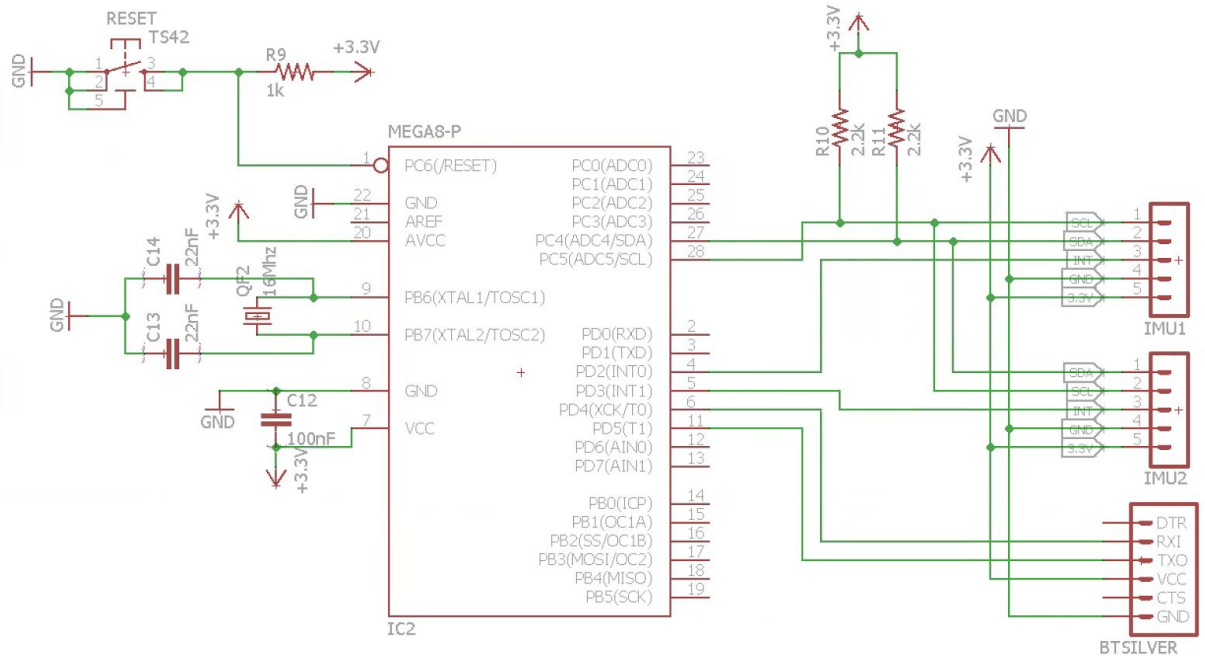


Figure 2. Control and Seniors Schematic

(1) Microcontroller

Inputs:

a. 3.3 V from power supply
b. IMU sensor data (I2C interface)
c. Bluetooth module data (SPI interface)
d. Push button switch

Purpose:

a. The microcontroller is the hub of the device. It will control the state of the IMU sensors (transmitting data or not) and will determine the frequency of acceleration

and rotation data collection. The microcontroller will also control the state of the bluetooth module, and transmit data from the IMU to the bluetooth module. It will also receive input from the push button for powering on, powering off, and resetting the system. It will provide device status through a LED, which will show if the device is on or off, as well as whether it is actively transmitting data or not.

Outputs:

a. IMU control signals (I2C interface)
b. Bluetooth control signals (SPI interface)
c. Acceleration and rotational data to bluetooth module
d. LED indicator

(2) Wireless Communication

Inputs:

a. 3.3 V from power supply
b. Microcontroller data (SPI interface)
c. PC device data (Bluetooth protocol)

Purpose:

a. The wireless communication block is a single bluetooth transmitter that will allow acceleration and rotation data to be transferred from the wearable device to the PC device. Acceleration and rotation data received from the microcontroller will be sent to the PC device through the bluetooth protocol. Data from the PC, such as control signals to shut down the device then need to be transferred back. The wireless communication module will also be able to receive and send this data to the microcontroller.

Outputs:

a. PC device
b. Microcontroller

iii. Sensors Subsystem

The sensors subsystem consists of two IMU sensors that collect rotational and acceleration data which is transmitted to the control subsystem.

(1) IMU sensor

Inputs:

a. 3.3 V from power supply
b. Microcontroller control signals (I2C interface)

Purpose

a. The IMU sensors will collect acceleration and rotation data for the device. This data will be used to calculate the positional changes of the device. The calculations occur on the microcontroller as we don't want to rely heavily on PC or mobile devices to handle calculations as some users may not have very robust systems.

Outputs:

a. Acceleration and rotation data to microcontroller (I2C interface)

iv. Power Subsystem

Figures 3, 4, and 9 detail the power subsystem consisting of a charging circuit, Lithium Polymer battery, power switching circuit, buck converter, and undervoltage lockout circuit.

We chose to use a Lithium Polymer battery because it is lightweight and has high energy density compared to alternatives, which was important to us because we sought to minimize the footprint of our device. This does come at a cost, however, as lithium polymer batteries can explode if misused. If this device ever becomes available to the public, it is crucial to include a safety statement regarding this issue in the user manual to prevent any possible exploding events due to misuse.

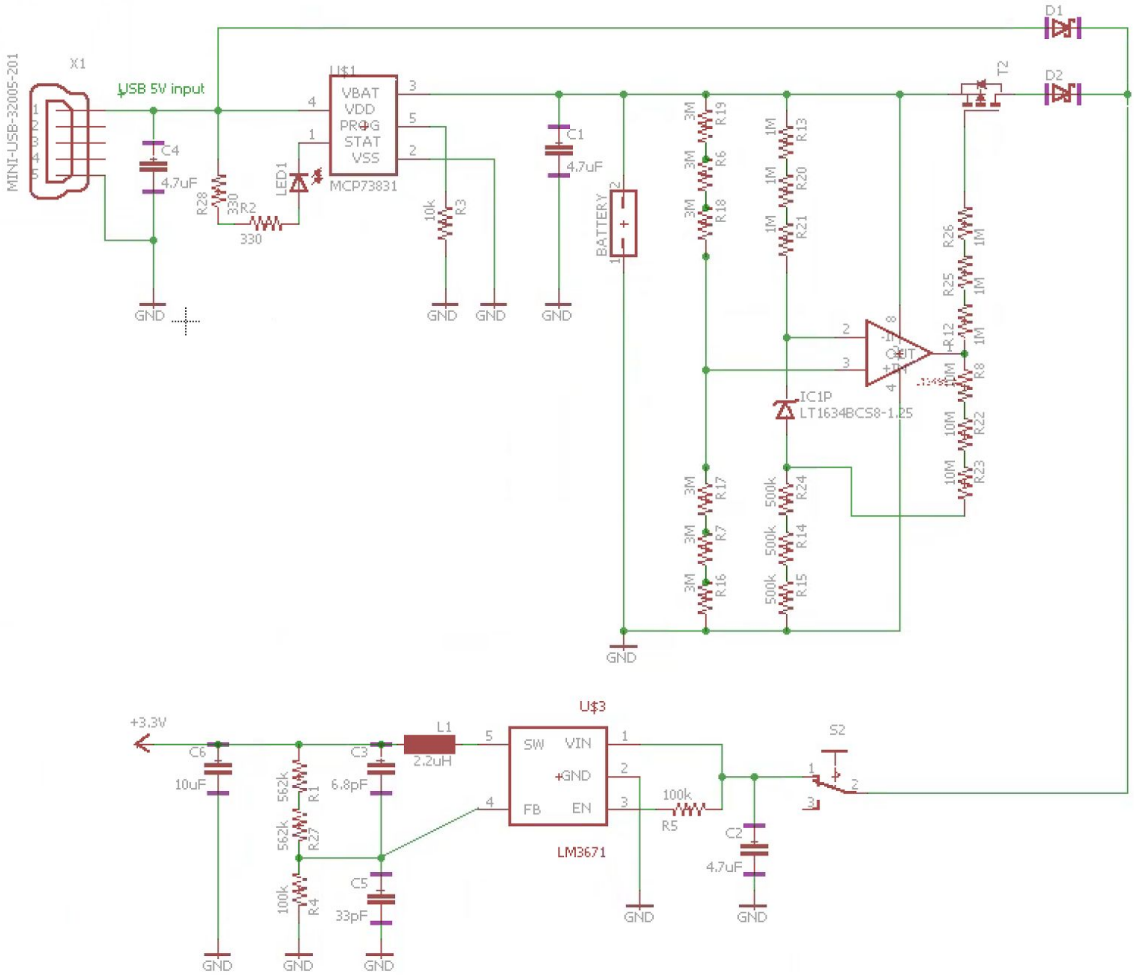


Figure 3. Power Subsystem Schematic

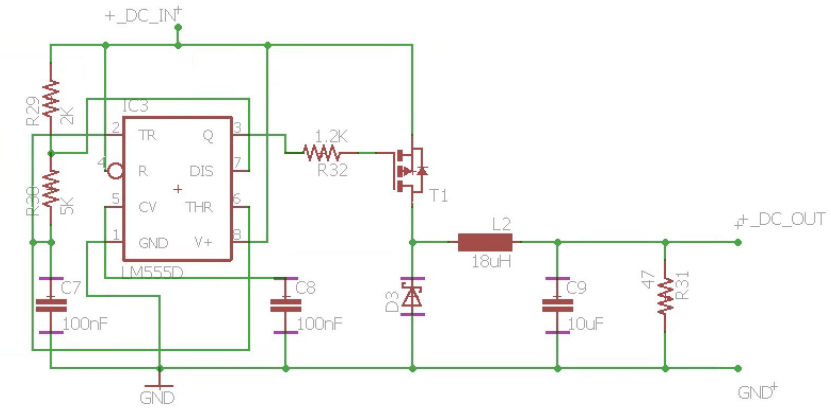


Figure 4. Buck Converter Schematic

There were two unknown resistor values we needed to calculate in figure 3. For the value of R2, a simple V=IR calculation of 5V/470Ω ≈ 10mA which is sufficient to drive a red LED. The value of R3 requires a more complex calculation since it depends on the intrinsic properties of the p-channel mosfet transistor. The equation below shows the current supplied by a p-channel transistor based on transistor characteristics.

$$i_{ds} = \mu_n c_{ox} (\frac{w}{l})(V_{gs} - V_t)^2$$

Ideally, based on max current draw, i_{ds} should be at least 48 mA. Given the battery voltage of 3.7 V, the resistor should be around 75 Ω to draw 50 mA of current.

Table 1 shows the maximum current draw of each component as well as the resulting total current draw of the device. The device should function for at least 5 hours under maximum usage to ensure the user does not need to charge the device more than once a day. Assuming an overhead of 100% (worst case scenario), the maximum current draw is 64mA. The following power calculation yielded the maximum power draw of this device under 5 hours of usage.

5 hours * 64mA = 320mAh

Thus we needed a battery which had a capacity of at least 320mAh, and to be on the safe side we chose a battery rated at 350mAh.

Device	Max Current Draw
Microcontroller	12 mA
IMU A	4 mA
IMU B	4 mA
Bluetooth Module	12 mA
Total	32 mA
With 50% overhead	48 mA

With 100% overhead	64mA

Table 1. Current Draw

(1) Charging Circuit

Inputs:

a. 5 V DC from mini-USB

Purpose

a. The charging circuit will provide power to the control and sensor subsystems by switching between battery and AC adapter as necessary. On normal operation, where the device is unplugged from a 5V DC source, the charging circuit will draw current from the rechargeable battery. If the battery has a low charge, the low battery LED will light up to prompt the user to recharge the device.

Outputs:

a. Variable DC to recharge battery (current and voltage depend on charging conditions)
b. LED to indicate low battery charge

(2) Power Switching Circuit

Inputs:

a. 5 V/0 V USB DC
b. 3.5- 4.2 V Battery DC

Purpose

a. The power switching circuit is made up of a p-channel MOSFET and 2 diodes to switch between either the battery or USB inputs. If the battery is charging, the load should only draw from the 5 V source, and not the battery. The transistor gate is controlled by the USB source. When the USB source is switched off, the gate allows the current from the battery to flow through to the load.

Outputs:

a. 3.3 V Regulator

(3) Buck Converter

Inputs:

a. 3.3 V - 5 V DC from battery or USB source

Purpose:

a. The buck converter should take in 3.3V - 5V and output 3.3V to the rest of the circuit. The buck converter should be at least 80% efficient to maximize battery life. For the final PCB

Outputs:

a. 3.3 V DC

(4) Undervoltage Lockout

Inputs:

a. 0-5V DC from battery

Purpose:

a. The UVLO (figure 9) prevents battery usage when the battery drops below 3.5V to prevent deep battery discharge. For lithium polymer batteries, deep discharge can permanently damage the battery or reduce capacity over time. The UVLO circuit has a comparator that controls a PMOS for switching the load on or off. The comparator takes in the battery voltage and a compares it to a shunt reference. When the battery voltage drops below the reference voltage, the comparator switches the PMOS so that the load no longers draws current from the battery. The UVLO circuit uses resistors in the megohm range to reduce current draw for longer battery life. A simulation of the working UVLO is shown in figure 8.

Outputs:

a. 3.5-4.2V DC from battery

v. Microcontroller Software

This software component takes in both the Digital Motion Processor (DMP) and raw data from the two inertial measurement units (IMUs) and passes this data to the computer for further processing. The software first sets up the connection baud rate for the bluetooth and initializes the offsets for both IMUs. The software then goes into a loop every ten milliseconds for data collection and passing. In the loop, the software requests quaternions, acceleration and euler angle data from the fifo buffer in the IMUs and requests the bluetooth module to pass data on to the PC. The software also calculates a 22 byte package (table 2) from the quaternions data for the Processing software to graph the 3D model of the movement. To ensure stability, during every loop the software checks the connection with the PC and IMUs, and will not update the 22 byte package if either or both do not have a connection. The diagram for this is shown in figure 5.

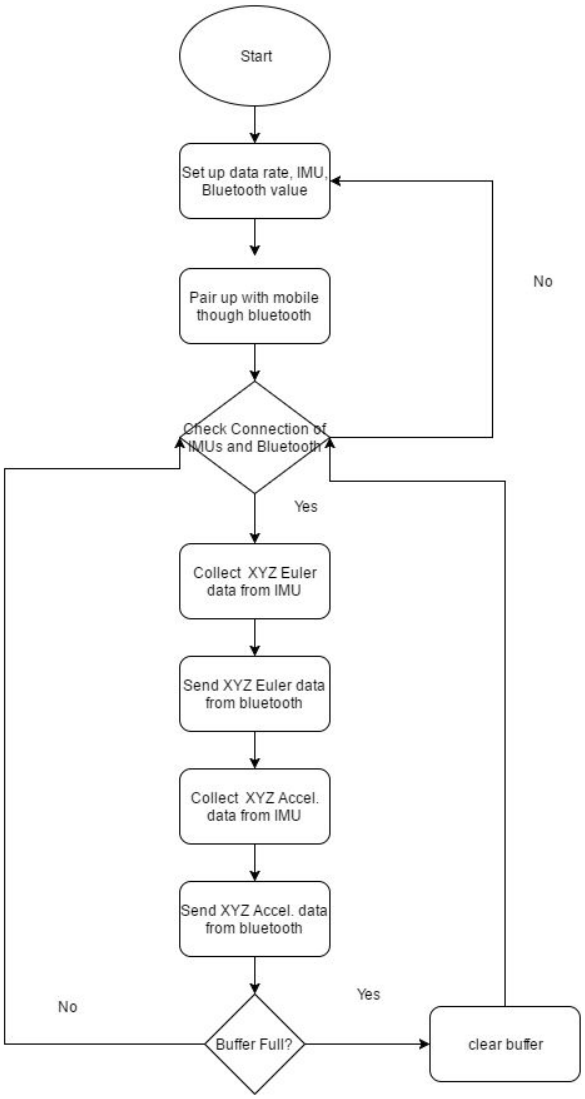


Figure 5. Microcontroller software flowchart

Byte	Description of value
0x00	Starting byte '$' for recognition
0x01	Starting byte '0x02' for recognition
0x02	First byte of quaternion angle for IMU 1
0x03	Second byte of quaternion angle for IMU 1

0x04	First byte of quaternion X axis for IMU 1
0x05	Second byte of quaternion X axis for IMU 1
0x06	First byte of quaternion Y axis for IMU 1
0x07	Second byte of quaternion Y axis for IMU 1
0x08	First byte of quaternion Z axis for IMU 1
0x09	Second byte of quaternion Z axis for IMU 1
0x10	First byte of quaternion angle for IMU 2
0x11	Second byte of quaternion angle for IMU 2
0x12	First byte of quaternion X axis for IMU 2
0x13	Second byte of quaternion X axis for IMU 2
0x14	First byte of quaternion Y axis for IMU 2
0x15	Second byte of quaternion Y axis for IMU 2
0x16	First byte of quaternion Z axis for IMU 2
0x17	Second byte of quaternion Z axis for IMU 2
0x18	Ending byte ‘0x02’ for recognition
0x19	Packet count for processing
0x20	‘\r’ carriage return for serial port
0x21	‘\n’ newline for serial port
Bytes 0x02-0x17 will then be repeated as many times as necessary	

Table 2. Data byte mapping for sensor data packet transmission via bluetooth

vi. 3D Modeling Software

This software component takes in the 22 byte quaternions data packet shown in table 2 and draws the 3D model of the movement in Processing 3.0. The software uses OpenGL library for drawing and toxic library for 3D model calculation. This software first draws the movement guide which the user needs to follow in a red bar. Next, the software does calculations on the quaternions bytes received from the bluetooth and draws the approximate position of the IMUs from the quaternions data to show the patient movement. The screenshot of the straight leg raise and leg extensions Processing model in action are shown in figures 12 and figure 13.

3. Design Verification

i. Overview

Design requirements and verification is detailed in Appendix B. Our System successfully performed all the necessary functions.

ii. Inertial Measurement Unit

The most important part of our device is the IMU measurement, especially the Z axis which is where both leg exercises revolve around. To verify the IMU performance of receiving the correct euler degree data, we put the IMU in a flat and 90 degree position in the Z axis and verificated the eugler degree we got. We got between 0.01 and 0.00 for the IMU in the flat position and between 88.00 to 88.99 for the IMU in the 90 degree position of the Z axis. This is within 5% accuracy which was required. The IMU moves according to the physical movement which was visually verificated in the 3D modeling program, showing that it has no problem with smooth data measurement.

4. Cost

i. Labor:

A lot of work went into our project in order to produce a working device. Table 3 shows the approximate cost of labor of our project.

Partner	Hourly Rate	Total Hours	Total (x2.5)
Titus Fong	$50	100	$12500
Mengda Qi	$50	100	$12500
Caleb Klaus	$50	100	$12500
Total	$150	300	$37500

Table 3. Labor Costs

ii. Parts List:

This device consists of many components, each of which comes with a price. We sought to balance price and convenience (availability, documentation, etc) when choosing parts. Table 4 lists the cost of the components which were used in our project.

Item	Parts	Quantity	Unit Price	Total
Microcontroller	ATmega328P	1	$1.43	$1.43
Bluetooth Module	nRF51822	2	$17.95	$35.9
Inertial Measurement Unit	MPU-6050	2	$39.95	$79.9
Charge Management Controllers	MCP73831	1	$1.28	$1.28

Linear Regulator	LM1117	1	$1.65	$1.65
Printed Circuit Board (PCB)	Designed by us Manufactured by PCBway	10	$6.65	$66.50
Protoboard		2	$5	$10
PMOS Transistor	DMG1013UW	1	$0.99	$0.99
Total				$153.73

Table 4. Parts List

Adding the total values of table 3 and table 4, the grand total cost of our project comes out to **$37,653.73**.

5. Conclusions

i. Accomplishments

In conclusion, we successfully designed and created a health and fitness device that tracks medical leg exercises. Our PCB successfully transmitted the movement data collected from the IMUs to the PC. We are also successfully created a 3D animation with our software model on PC. We meet all the requirement mentioned in the verification table. This project received 3rd place in the 2016 Cozad New Venture Competition and has been accepted in the 2016-2017 iVenture, Polsky, and Summer@CIE Accelerator program for further development.

ii. Uncertainties

One of the challenges that we encountered was data processing and filtering. The data received had problems with motion drafting. After some research on this problem, we were able to set the offset of the IMU to address the drafting problem. The drafting in the IMU is now undetectable

by eye. We also encountered a system freezing problem. By clearing the buffer in IMU after every single loop and lowing the sample rate, we were able to collect data continuously for at last ten minutes.

iii. Ethical Considerations

Due to the fact we created a product which could be potentially harmful to the public because of the use of electrical components, we accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and are committed to promptly disclose factors that might endanger the public or the environment. Since this product is tied to the medical field, appropriate federal and state regulations were followed. We worked with an external team to ensure that all HIPAA rules were closely followed in terms of data storage and personal records maintenance. We also followed the IEEE code of ethics in this project. We strived to be honest in our estimates to the best of our knowledge, and were open to constructive criticism from our professors, TAs, and peers. We did our best to not discriminate by considering all demographics as our target customer. We were always willing to help out our colleagues when necessary and offered our honest opinions through peer review to help them succeed.

iv. Future Work

The stability is one of the major issue that we have to address for future development as stated above. The other work we will do in the future is to design a smaller PCB for the device for normal usage since the device we have is too large. We printed a larger PCB to ensure all components could be soldered easily. However we designed a more compact PCB (figure 11) which can be printed in the future. We will also look into installing two bluetooth modules so that the two IMUs do not have to link with each other to reduce the footprint of the device. We will also develop a mobile app to keep tack of the patient improvement on these medical exercises. This work will be done in the near future while we are participating in the 2016-2017 iVenture, Polsky, and Summer@CIE Accelerators. In our business plan, we are planning on launching the product in the 3rd quarter of 2017 for hospital and clinic to use.

References

1. “A Model To Project The Supply And Demand Of Physical Therapists 2010-2020”. American Physical Therapy Association. Web. 28 Feb. 2016
http://www.apta.org/WorkforceData/ModelDescriptionFigures/

2. "ACSM | Fact Sheets." *ACSM | Fact Sheets*. Web. 28 Feb. 2016.
https://www.acsm.org/public-information/brochures-fact-sheets/fact-sheets

3. "Arthritis-Related Statistics." *Centers for Disease Control and Prevention*. Centers for Disease Control and Prevention, 2016. Web. 28 Feb. 2016.
http://www.cdc.gov/arthritis/data_statistics/arthritis-related-stats.htm

4. "Arthritis-Related Statistics." *Centers for Disease Control and Prevention*. Centers for Disease Control and Prevention, 2016. Web. 28 Feb. 2016.

http://www.cdc.gov/arthritis/data_statistics/arthritis-related-stats.htm

5. Dr Campbell. "*J Epidemiol Community Health* 2001." Web. 28 Feb. 2016
http://jech.bmj.com/content/55/2/132.full

6. "Result Filters." *National Center for Biotechnology Information*. U.S. National Library of Medicine. Web. 28 Feb. 2016.
http://www.ncbi.nlm.nih.gov/pubmed/8234458

7. "Medicare Home Health Rates Set for 2014." *Medicare Home Health Rates Set for 2014*. Web. 28 Feb. 2016.
http://www.asha.org/News/2013/Medicare-Home-Health-Rates-Set-for-2014/

8. "Knee Conditioning Program". American Academy of Orthopaedic Surgeons. Web. 28 Feb. 2016
http://orthoinfo.aaos.org/PDFs/Rehab_Knee_6.pdf

9. "Steps to Success: A Guide to Knee Rehabilitation". Carticel Web. 28 Feb. 2016
http://www.kneeclinic.info/download/Carticel_ACI_Rehabilitation_Guide.pdf

10. "Rotator Cuff and Shoulder Conditioning Program" American Academy of Orthopaedic Surgeons. Web. 28 Feb. 2016
http://orthoinfo.aaos.org/PDFs/Rehab_Shoulder_5.pdf

11. "Hip Conditioning Program" American Academy of Orthopaedic Surgeons. Web. 28 Feb. 2016
http://orthoinfo.aaos.org/PDFs/Rehab_Hip_3.pdf

Appendix A: Additional Figures

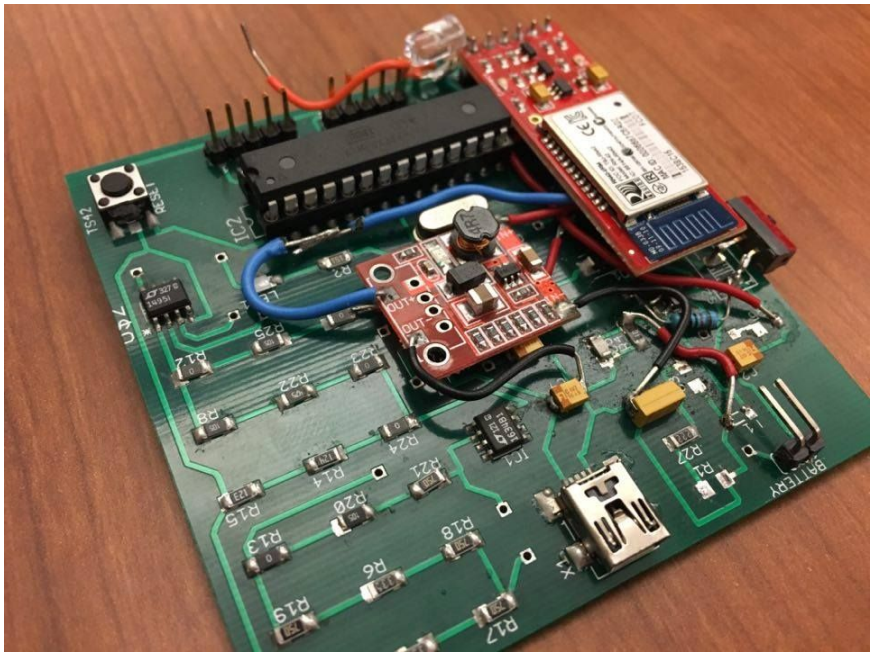


Figure 6. ExoWear Physical Device

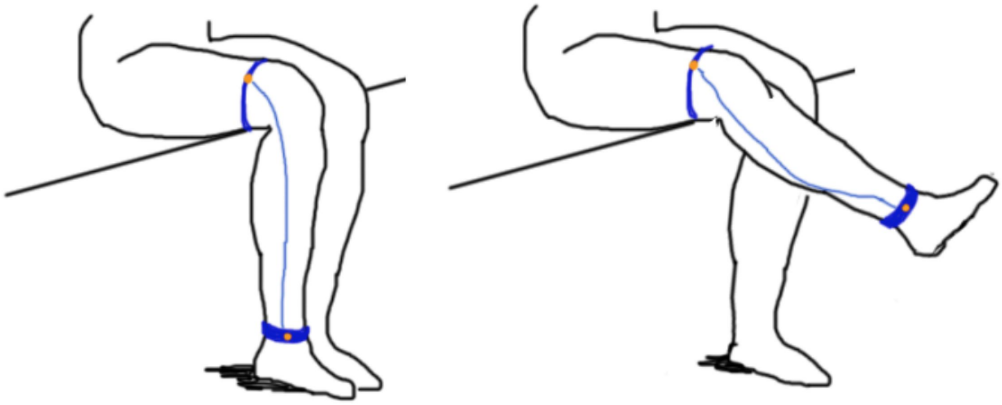


Figure 7. Physical Application

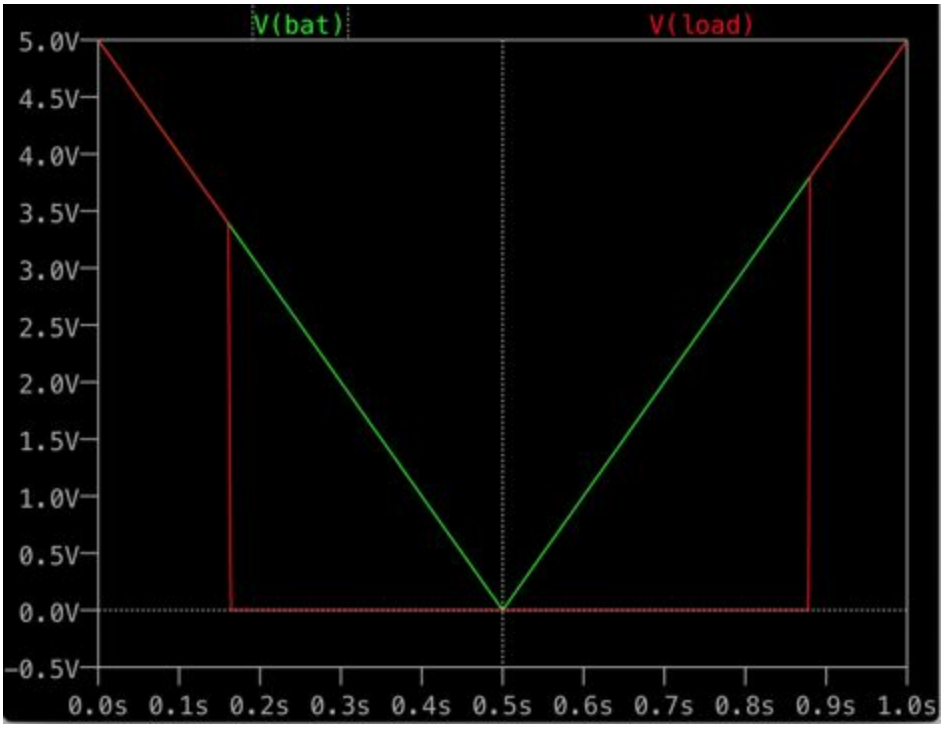


Figure 8. UVLO Simulation

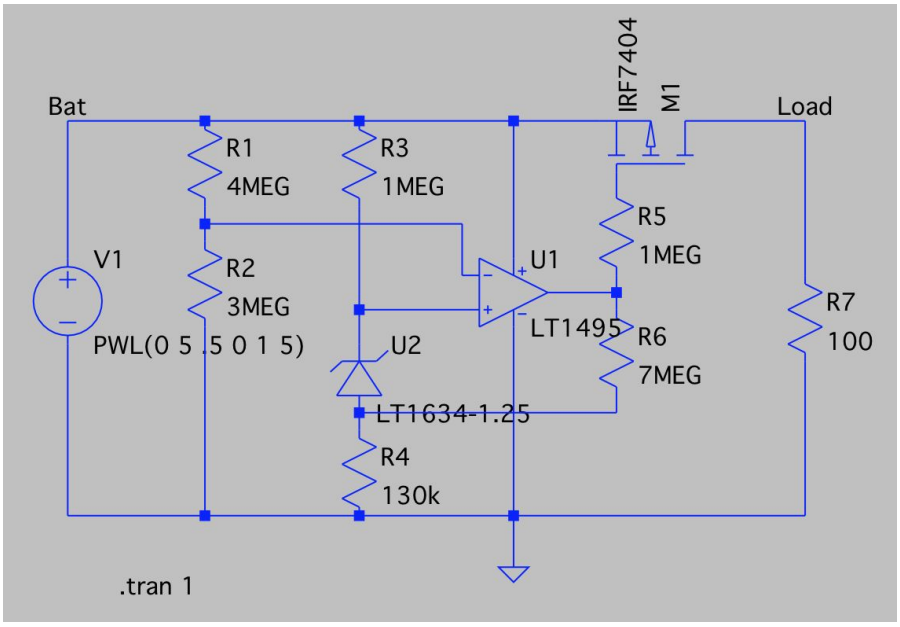


Figure 9. UVLO Schematic

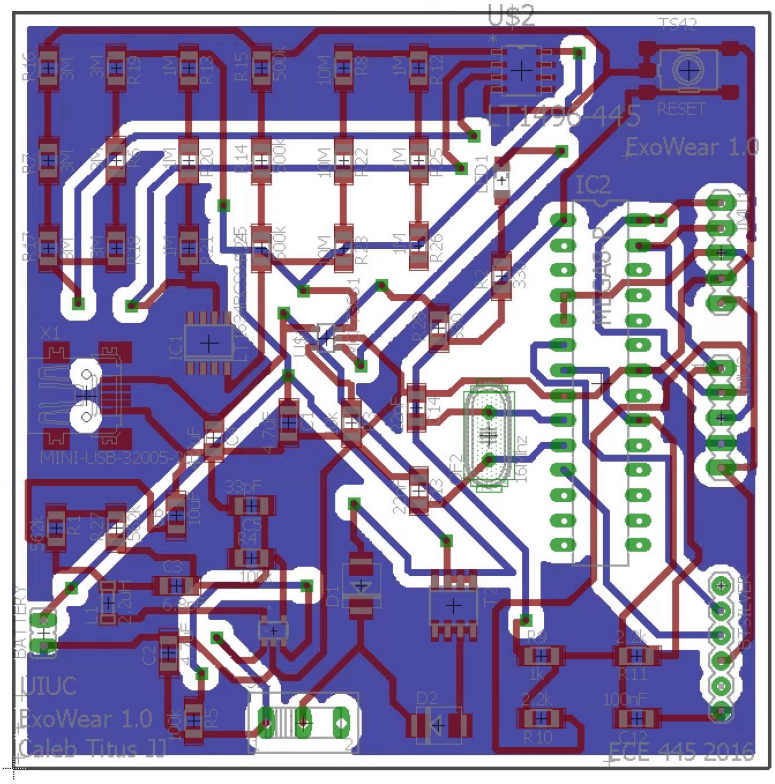


Figure 10. PCB Design

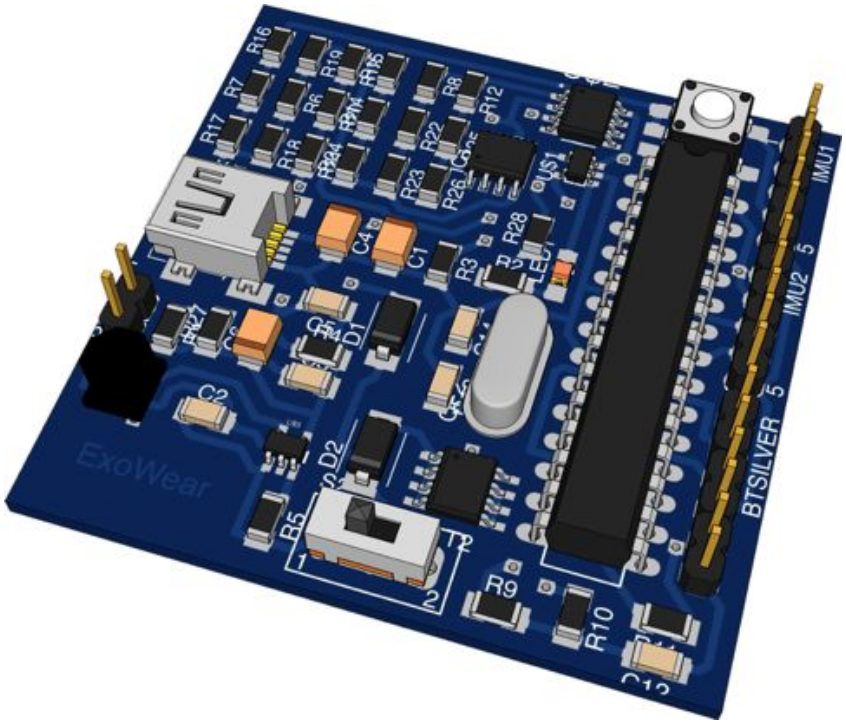


Figure 11. Compact PCB 3D model

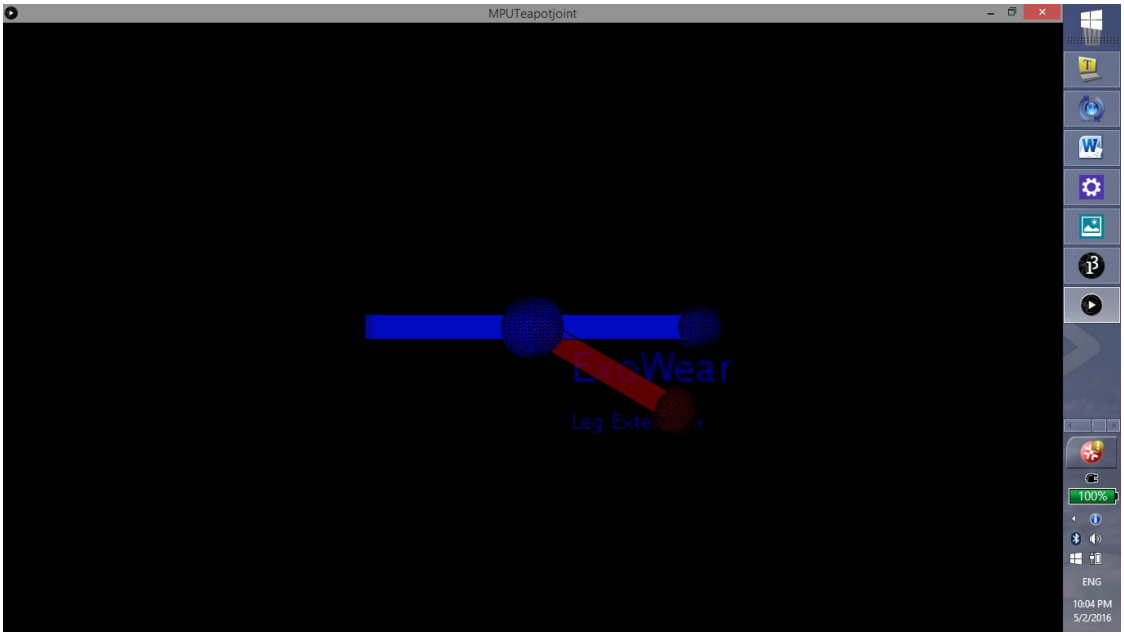


Figure 12. Leg Extension in 3D Processing

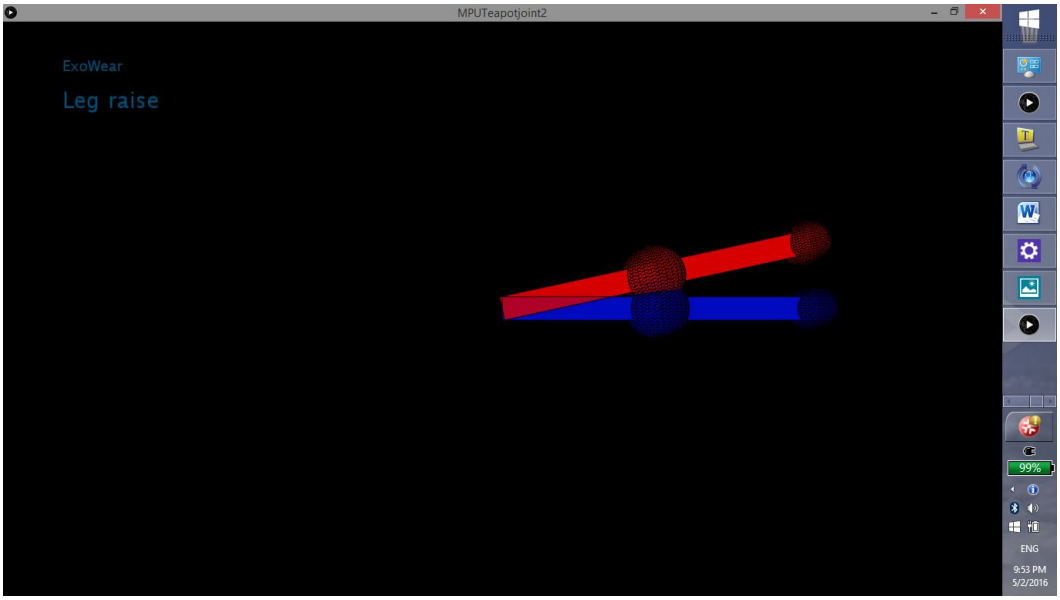


Figure 13. Leg Raise in 3D Processing

Appendix B: Requirements and Verification

Requirement	Verification	Points
Power		
Buck Converter 1. From input of 5 V ± 0.2 V, output of 3.3 V ± 0.1 V with max load of 100 mA	1. Verification Process for Item 1: a. Attach 35 ohm resistor as load b. Attach oscilloscope across load c. Set NMOS gate voltage to 31.25 kHz square wave with 59.375% duty cycle d. Ensure output voltage remains between 3.2 V and 3.4 V	**10**
Battery 1. Battery must store 350 mAh, ±30 mAh tolerance, of charge 2. Battery must maintain charge when device is not in use. No substantial current leak (up to 10% capacity in 5 days) should occur. 3. Device functions for 5	1. Verification Process for Item 1: a. Attach 5.5 ohm resistor bank as load b. Measure I and V at 5 minute intervals c. Terminate test when any Vcell 3.3 V d. Perform midpoint Riemann summation e. Ensure 350 mAh, ±30 mAh extracted 2. Verification Process for Item 2: a. Fully charge battery b. Unplug charger from wall outlet c. Allow to sit for 5 days d. Measure cell voltages e. Ensure battery has not discharged beyond 10% of max value 3. Verification Process for Item 3:	**3**

hours	a. Fully charge battery b. Unplug charger from wall outlet c. Turn on device d. Wait 5 hours e. Ensure device still functions	
Charger 1. Battery must fully charge to 350 mAh ±30 mAh in less than 90 minutes	1. Verification Process for Item 1: a. Unplug charger from wall outlet b. Fully drain battery c. Plug charger into wall outlet d. Wait 90 minutes e. Ensure battery contains 350 mAh, ±30 mAh	**2**
Under Voltage Lock Out 1. Battery is cut off from the rest of the device when battery voltage drops below 3 V ± 0.1 V	1. Verification Process for Item 1: a. Fully charge battery b. Unplug charger from wall outlet c. Connect battery to device d. Wait until device powers off from lack of power e. Measure battery voltage f. Ensure battery voltage is 3V ± 0.1 V	**15**
Power Switching Circuit 1. Voltage output switches to 5 V ± 0.2 V when Vin source is 5 V ± 0.2 V 2. Voltage output	1. Verification Process for Item 1: a. Allow the battery to be fully charged b. Attach 5V ± 0.2 V DC voltage supply to 5V Vin c. Output from circuit should be 5V ± 0.2 V and current draw from battery should be ≤ 0.1 mA	**5**

switches to 3.7 V ± 0.1 V when Vin source is open	2. Verification Process for Item 2 a. Allow the battery to be fully charged b. Remove Vin source c. Ensure there is a 3.7V ± 0.1 V power supply to the linear regulator from the battery	
Control		
Wireless data transmission 1. Functions for 3.3 V ± 0.1 V for Vin 2. RF bluetooth range is at least 5 meters 3. Wirelessly transmits data at 115200 ± 1000 bps	1. Verification Process for Item 1: a. Attach 200 ohm resistance between leads b. Request bluetooth RF broad (slave) to send test data to computer (master) c. Attach variable voltage supply to Vin d. Sweep from 3.2 V to 3.4 V and ensure digital output remains original value 2. Verification Process for Item 2: a. Request bluetooth RF broad (slave) to send testing data to computer (master) b. Move from the computer (master) to 5 meter away and ensure digital output remains of original value 3. Verification Process for Item 3: a. Request bluetooth RF broad (slave) to send test data to computer (master) b. Send 115200 bits (14,400 bytes) of data	**2.5**

	c. After 1 second, ensure 115200 ± 1000 bits received by computer	
Microprocessor: Digital Input/Output 1. Digital 0 corresponds to Vin $\leq$ 0.2 V 2. Digital 1 corresponds to Vin $\geq$ 3.0 V 3. Must have 4 pins	1. Verification Process for Item 1: a. Power controller with 3.0 V b. Attach all digital pins to 0.2 V c. Upload code setting all digital pins to INPUT and printing the values via Serial d. Ensure value obtained 0 2. Verification Process for Item 2: a. Power controller with 3.0 V b. Attach all digital pins to 3.0 V c. Upload code setting all digital pins to INPUT and printing the values via Serial d. Ensure value obtained is 1 3. Verification Process for Item 3: a. Do steps 1 and 2 for all 4 pins	**1**
External Device (PC)		
Data modeling on PC 1. Display user's movement on PC in real-time 2. Show training movement on PC	1. Verification Process for Item 1: a. Strap device on b. Turn device on c. Request IMU data d. Display IMU output data on PC e. Visually ensure angle is same as angle of knee.	**9**

which the user needs to follow.	2. Verification Process for Item 2: a. Display a bar which starts at 0 degrees b. Verify bar slowly goes up to 90 degrees, then back to 0, and repeats	
Sensors		
Inertial measurement unit 1. Functions for 3.3 V ± 0.1 V for Vin 2. Rotational angle data from the IMU is within 5 degrees of actual rotational angle	1. Verification Process for Item 1: a. Attach 200 ohm resistance between leads b. Keep IMU still to simulate no motion c. Attach variable voltage supply to Vin d. Sweep from 3.2 V to 3.4 V and ensure digital output remains at the original value 2. Verification Process for Item 3: a. Attach two IMU together at 0 degrees angle b. Request data from IMU for accelerometer, angular rate sensor and Digital Motion Processing data c. Move IMUs with relation to each other to create an angle d. Measure the angle between the 2 IMUs with a protractor e. Ensure the two IMUs have output angular rate and Digital Motion	**2.5**

	Processing angle values that are within 5 degrees of the measured angle	