Design 3 Technical Memo

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ENGG 3100, Group Mon1-08
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1 Introduction

Understanding the forces that act on the knee are crucial to the success on the design. Once the forces on the knee are understood, they can be detected an then the information ca be used.

The bones that are important to consider during an ACL tear are the Tibia and the Femur. These bones will be significant in modelling the human knee as a two member system, to understand what forces are acting on the knee at certain angles of bend. While the Fibula articulates with the Tibia, it does not directly come in contact with the ACL, and for the purposes of calculation, it can be disregarded for the purpose of modelling as a two member system.

Modelling the knee as a two member system, as well as using known properties and dimensions of muscles, ligaments, and bones, a force threshold will be able to be determined, as the purpose of this device is to detect when a force on the knee has surpassed said threshold. The threshold will be determined to be equivalent to the stress on the ACL to tear it, with a safety factor to comfortably have a range of forces, without impeding on play.

While mechanics and biomechanics are important fields to consider when building this device, a bulk of the technical effort will be put towards circuit board design, signal processing, and coding the microprocessor, and monitoring system for coaches.

The features of the microprocessor are important to be considered when creating this device to detect dangerous ACL forces. As a result, the interactions between the sensors, microprocessor, and the transmitting device to the athlete monitoring device will need to be designed and implemented.

Furthermore, the microprocessor and the athlete monitoring system will need to be coded. The microprocessor needs to be coded such that it can receive signals from the sensors that are used, perform some calculations to determine the forces on the ACL, and if the force has passed a set threshold, found using the mechanical analysis, the microprocessor will transmit a signal to the monitoring system a coach has.

Finally, the monitoring system will need to be designed and coded. It will most likely be an iOS or an Android app, so a coach can have a smart phone with the data of all their players readily available during play.

2 Problem Statement for Calculations

The most important problem that needs to be solved is how to translate an external force on the leg to an internal force on the ACL. This can be achieved by investigating the moment about the femoral head, and finding the stress acting on the joint. To determine how the force on the ACL changes based on the angle of bend of the knee, the knee joint can be modelled as a two member system and kinematic and dynamic equations of the system can be analyzed. Once the forces acting on the ACL have been evaluated, a force threshold can be determined for the device to detect.

Once the force threshold has been found, the circuit board can collect information from a pressure sensor that fits in an athlete's shoe and and a flex sensor that will fit in the actual knee sleeve. The pressure sensor in the shoe will communicate using Bluetooth to the flex sensor circuit on the knee to calculate how much force is being exerted on an athlete's knee at a given time. The main circuit on the knee will be able to communicate via Wifi to a bystander on the sidelines that will send notifications when a player has crossed the determined safe threshold.

3 Background Information

A pressure sensor embedded in the shoe will be able to determine the force of the step that the athlete exerts on their leg when walking. The flex sensor on the knee will be able to determine how much an athlete's knee is bent. Using these two measurements, the amount of force on an athlete's ACL will be able to be calculated.

Using Mechanical force analysis, a force threshold for a dangerous movement has been determined to be approximately 1500 N (see Appendix A.1).

Once that information has been acquired by the sensors, the information can be processed by the microprocessor and transmitted to the coach receiving information on the sidelines.

If an athlete has passed the allowable force threshold, the coach will receive a notification, and will be able to make a decision to remove a player from a game in interest of their health.

4 Assumptions

Within the moment calculations, the femur is considered to be a fixed point
This assumption allows the moment calculations to be done with respect to the femur similar to how the sensors will analyze the output.
The maximum force that can be exerted onto the ACL is 1500 N
The 1500N has a safety factor of 4/3. This is the maximum allowable stress the sensors will allow before transmitting that a dangerous movement has occured and an athlete is exerting an excessive force on the knee.
The thickness and length of the brace will be 4mm and 30cm respectively
A 4mm thickness will allow for a very lightweight and durable material that will be able to house the wires and work with other braces. The 30cm length will be the standard length capable of covering the knee while allowing proper sensor detection.
21.875 hours is the maximum wear time without charging
With the battery time and power consumption the brace will be able to work for 21 hours consecutively before a charge is needed. This ensures players are able to wear the brace during practise and a game.
0.8 ms to obtain all data from one knee brace
From each knee brace it will take the coach 0.8 ms to receive the data input from all the sensors of 1 athlete. This allows for a fast transfer of information between the athlete and coach with minimal wait time.
Average compression of the brace will be 25mmHg on the athlete
25mmHg is an experimental value found to best control venous blood in a knee brace [1] for maximum brace benefits
Assume zero initial conditions
All sensors will be calibrated to zero as soon as the athletes puts on the device and turns it on.

5 Material Properties

A compression knee brace will be covering the knee, which is housing the main microprocessor. The main material used within this brace will be a knitted elastic fiber that will be able to be used in addition and under regular knee braces that are used for protection. This compressive brace will be worn continuously during sporting activities. The compressive brace's elasticity will allow the brace to stay in place. Knitted fabrics allow for support, high breathability, and the prevention of skin irritation. The knitted fabric in use will be a commercial PS-K with an area density of 613.33 g/m^2, thickness of 1.98mm [2]. This material has tensile properties in both the vertical and cross sectional direction which can be seen in Table 1.

Load Direction	Breaking Load (N)	Breaking Extension %	Modulus (N)
Vertical	453.4	43.6	169.9
Cross Sectional	109.4	484.8	4.37

Table 1: Material Tensile Properties of commercial PS-K knitted elastic material [2]

6 Engineering Principles Governing Safety and Functionality of the Design

Determining parameters of the system was done by first taking a biomechanical approach and calculating maximum allowable forces exerted on the ACL from the femur and tibia. Mechanical analysis was done to ensure a safe allowable stress was calculated the ACL can withstand without causing injury to the individual. The brace itself if to be created from a compressive material, therefore tension and compression forces must be taken into account to ensure the product can be used safely without inhibiting regular blood circulation. As this device will be using electrical components, circuit diagrams were created to obtain values of voltages needed to supply electrical components. Types of batteries used within the design were assessed for safety in the given applications from external forces, as well as the safety of the battery being within such close proximity to the individual wearing the device. Force sensors are also integrated within the shoe of the athlete for measurement purposes. All of these sensors must be placed in such a way so accurate data measurements can be taken. Comfort of the individual must also be taken into account for the device not to be detrimental to any athletic performance.

7 Executing Engineering Calculations

This device is classified as a Class II Medical device as specified by the FDA regulations [3]. This device is actively monitoring and tracking users motions based on the sensors included with this device.Other codes and regulations what have to be followed include the Acceptance of Electrical Equipment in Canadian Provincial and Territorial Jurisdictions through the Electrical Safety Authority for the electrical components, ISO 14971 and IEC-60601-1-1 for risk management standards within electronic medical devices. All of these standards must be followed for the creation of a safe device.

7.1 Mechanical Analysis of the Knee as a 2 Member System

In order to create a accurate model of a human knee the Tibia and Femur were considered as members as the structure of a bone will transmit forces that will cause the ACL to break. The ACL is modeled as a soild body connecting the two members at a ridged angle. With spring connections (defined to only effect the system in tension) in the position of the PCL and MCL. The angle of the members is then systematically changed along with the solid model of the ACL in correlation with the research obtained.

By using the process to create a model it was able to accurately determine the effects on outside forces on the knee joint while in different positions. The forces applied were to the Anterior, posture, medial and lateral sides of the Tibia in turn. A torsion moment was then applied both Clockwise and counter clockwise to the tibia. All forces were applied 100 mm below the knee joint in correlation to where the senors will be in our design would end. In particular we were interested in how the bend angle of the knee, the valgus angle and the anterior distance/displacement of the Tibia from the Femur affected the rupture forces of the ACL

Through this modeling it is able to be concluded that there are multiple almost linear relations between bend angle of the knee and the rupture force of the ACL. The Medial and Lateral forces needed for ACL rupture during knee bend testing showed that damage would be done to the LCL or MCL while before the ACL is affected. When a torsion force is applied to the tibia it is also the LCL and MCL that will be damaged before the ACL, although if enough torsional force is applied to rupture the LCL and/or the MCL the ACL will be put at risk. If the LCL or and/or the MCL rupture from such a force our device has no way of detecting this damage and by extent protecting the ACL at this time.

See Table 2 for the complete data set of the anterior/posture forces that caused our model to rupture. It is these values with a factor of safety that our device will be designed to protect against through detection.

7.2 Circuit Design

The main goal of the circuit is to collect information that is required by the algorithm created to detect danger. The application consists of two circuits that communicate together using an SPI interface. Both circuits are powered by a chargeable battery. Hardware was implemented to charge these batteries and notify the user when battery levels are low. The first circuit will be placed by the knee. This circuit consists of a gyroscope, a sensor that reads the X Y and Z directions, and a flex sensor that reads the angle of the knee. The main objective of the first circuit or in other words the master is to collect data from the second circuit or the slave, and store the data into the Arduino chip for analyzing. Algorithms will be implemented into the ATMega chip (arduino) and collected data from all 5 sensors will be used to notify the coach if a wrong movement was committed. The Master circuit will communicate results with the coach through wifi that is provided by the ESP chip. ESP chip provides wifi communication with the user interface which is an application that the user can download through app store or the play store making it available on all platform. Coaches can download the application on their IPad and monitor their athletes. The second circuit will be placed by the foot. This circuit consists of 2 pressure sensors and a flex sensor. The main objective of this circuit is to collect information using the pressure sensors and the flex sensor, and provide the master circuit with the information needed for the algorithm to detect any injuries.

7.3 Circuit Board Communication

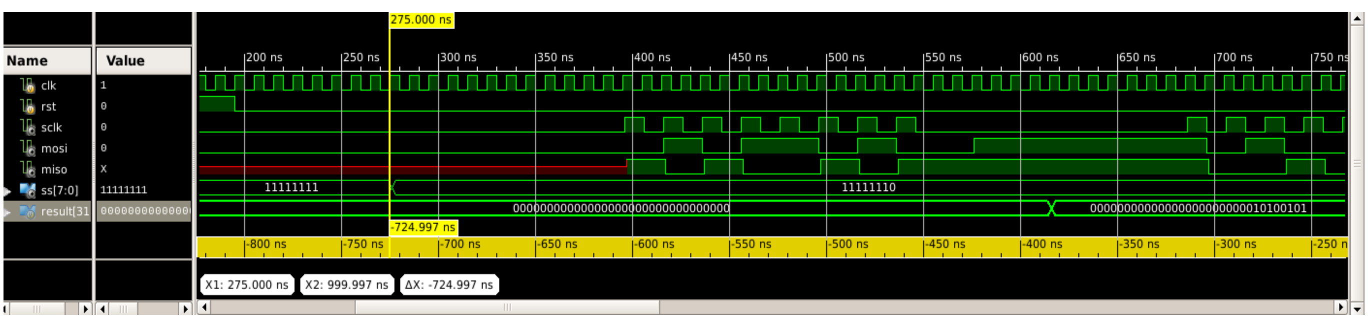

Figure 1: Communication Simulation

SPI communication will be used to transfer data from the master circuit to the slave circuit The Serial Peripheral Interface (SPI) bus is a synchronous serial communication controller specification used for distance communication, primarily in embedded systems. The SPI is a four-wire serial bus that communicates using the MOSI (Master Output, Slave Input), MISO (Master Input, Slave Output), SCLK (Serial Clock), and SS select (Slave Select). The waveform above was simulated to explain how IC chips will communicated together in this design. Data transmission begins on the falling edge of SS, then a number N of clock cycles will be provided. For this project a 16MHz clock cycle can be used, corresponding to the crystal clock implemented on the master circuit. The MOSI is driven with the output data payload. The data payload can contain either data and command. If MOSI contains a command, i.e. read command, after a programmed number of SCLK cycle, MISO will be driven with the serial data value read from the slave. This is how both circuits will send information. The SPI communication will be initiated by the ESP chip

7.4 Analysis of Compressive Force

The knee brace itself will produce a compressive force on the athlete wearing the device. This will produce tension that will be applied to the athlete. The pressure is given below.

$$P = \frac{T \cdot n \cdot K}{C \cdot W} \tag{1}$$

P = average pressure exerted on the leg (25mm/Hg)
T = Tension applied to the leg
n = number of layers (Assumed to be 1)
C = Limb circumference (cm)
W = Width of bandage (4 cm estimation)

The maximum compressive force found to help improve venous circulation is 25mm/Hg[2]. This gives a base calculation for the allowable tension on the leg considering various average leg circumferences. This measurement provides comfort and stability to the athlete achieved by the brace.

7.5 Error and Uncertainty

Within the calculations many assumptions were taken to create an average model. The approximate size of male football players were used to create the size of the brace. Maximum ACL force was approximated to be 2000N, with the length width and thickness of the human ACL was estimated from results obtained in literature. With all of these assumptions made a safety factor of 4/3 was implemented into the device to ensure any error can be minimized when working with a vast number of individuals.

8 Conclusion

The Mechanical analysis conducted, with the chosen Safety Factor allowed for a force value to be determined dangerous for the ACL. This was found to be approximately 1500N. This value can be used to program the microprocessor to detect for any dngerous forces.

The device is split into two different sub-system controlled by 2 different circuits. These circuits were calculated to consume 1.6 mAh. Results aided in the decision on which type of power supply will be used to power the system. A 3.3 V 35mAh battry will be used resulting in 21.875 hours of operation when fully charged.

As the device is split into two different sub-systems, separate code must be developed for the knee and shoe accordingly. All values must be sent to one device for calculation, so the shoe acts as the slave in a master-slave configuration with the knee.

Code for the shoe detects the values of the two pressure sensors and flex sensor within the shoe and sends a GET request to the knee. The shoe then sees if the knee system received the last message before sending another.

The knee detects the accelerometer and flex sensor values from the knee, along with reading in the values from the shoe, and calculates whether or not the current movement is risky for the player's ACL. If the device does detect a dangerous movement, the device will alert the coach immediately to get the player off the field as soon as possible.

References

[1] Scott, D. and McCormick. *Elastomer Compression* Beiersdorf Inc,August 26 2018.

[2] S. Perreira at al . *A study and properties of Novel fabrics for knee braces* Baletx Ltd, 2019

[3] *Medical Device Classification* U.S. Food and Drug Administration, 2018

Appendix A Calculations, Code, and CAD Modelling

A.1 Mechanical Analysis

To create a mechanical analysis the stress placed on the ACL due to anterior forces were considered as the main force causing an ACL to tear. The dimensions of an average ACL were taken [**?**] along with the force needed to rupture an average ACL. Using the length and radius the ACL was approximated as a cylinder with a constant volume, this was used to create a fixed variable when the length changed to determine the radius of the ACL through its range of motion. A cross sectional area for each of these different radii was then created for use in the stress derivation. A maximum stress value was determined using 2000N at anatomical position 0°of knee bend. Using this maximum stress value the maximum anterior force may be applied before rupture.

$$\begin{aligned} Volume(mm^3) &= \pi * Radius^2(mm^2) * Length(mm) \\ V &= \pi * 3.5^2 * 37.5 \\ V &= 1443.17(mm^3) \end{aligned} \tag{2}$$

$$\begin{aligned} Radius(mm) &= \sqrt{\frac{Volume(mm^3)}{\pi * Length(mm^2)}} \\ R &= \sqrt{\frac{51.97}{\pi * 36.5}} \\ R &= 3.55(mm) \end{aligned} \tag{3}$$

$$\begin{aligned} CrossSectionalArea(mm^2) &= \pi * Radius^2(mm) \\ Ca &= \pi * 3.55^2 \\ Ca &= 39.54.(mm^2) \end{aligned} \tag{4}$$

$$\begin{aligned} MaxStress(N/mm^2) &= \frac{RuptureForce(N)}{CrossSectionArea(mm^2)} \\ Ms &= \frac{2000}{38.48} \\ Ms &= 51.97(N/mm^2) \end{aligned} \tag{5}$$

$$\begin{aligned} MaxAnteriorForce(N) &= MaxStress(N/mm^2) * CrossSectionalArea(mm^2) \\ MF &= 51.97 * 39.54 \\ MF &= 1541.10(N) \end{aligned} \tag{6}$$

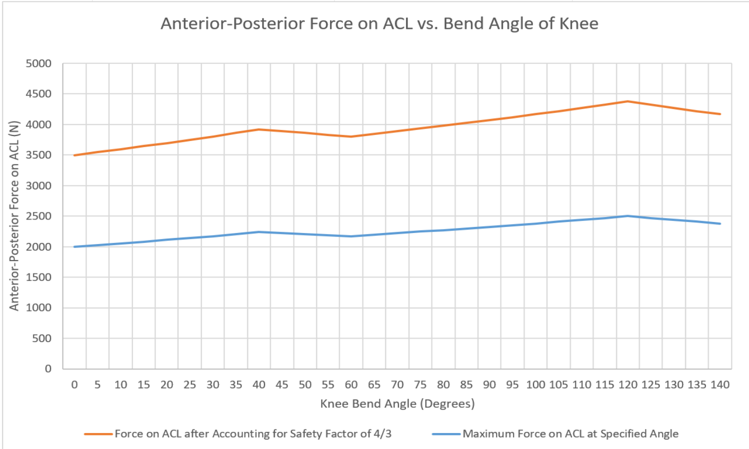

Figure 2: Anterior-Posterior Force on the ACL vs. Knee Angle

Table 2: Raw Data of Anterior-Posterior Force on ACL vs. Knee Bending Angle with a Safety Factor of 4/3

Flexion Angle (θ)	Length of ACL (mm)	Radius of ACL (mm)	Cross Sectional Area of ACL (mm^2)	Maximum Force at Specified Angle (N)	Force Accounting for Safety Factor (N)
0	37.5	3.5	38.48	2000	1500
5	37	3.52	39.00	2027.02	1520.27
10	36.5	3.54	39.53	2054.79	1541.09
15	36	3.57	40.08	2083.33	1562.50
20	35.5	3.59	40.65	2112.67	1584.50
25	35	3.62	41.23	2142.85	1607.14
30	34.5	3.64	41.83	2173.91	1630.43
35	34	3.67	42.44	2205.88	1654.41
40	33.5	3.70	43.07	2238.80	1679.10
45	33.75	3.68	42.76	2222.22	1666.66
50	34	3.67	42.44	2205.88	1654.41
55	34.25	3.66	42.13	2189.78	1642.33
60	34.5	3.64	41.83	2173.91	1630.43
65	34.125	3.66	42.29	2197.80	1648.35
70	33.75	3.68	42.76	2222.22	1666.66
75	33.375	3.70	43.24	2247.19	1685.39
80	33	3.73	43.73	2272.72	1704.54
85	32.625	3.75	44.23	2298.85	1724.13
90	32.25	3.77	44.74	2325.58	1744.18
95	31.875	3.79	45.27	2352.94	1764.70
100	31.50	3.81	45.81	2380.95	1785.71
105	31.12	3.84	46.36	2409.63	1807.22
110	30.75	3.86	46.93	2439.02	1829.26
115	30.37	3.88	47.51	2469.13	1851.85
120	30	3.91	48.10	2500.42	1875.85
125	30.37	3.88	47.51	2469.13	1851.85
130	30.75	3.86	46.93	2439.02	1829.26
135	31.12	3.84	46.36	2409.63	1807.22
140	31.5	3.81	45.81	2380.95	1785.71

A.2 Preliminary Arduino Code

```
// Code for shoe component to device
// This device is programmed via the Arduino IDE
// Reads signals from both pressure sensors and shoe flex sensor - sends it to other ESP8266

#include <ESP8266WiFi.h>

// Default password used for network client
const char *ssid = "ssid";
const char *password = "pass";

// Pins for sensors
int shoe_flex_pin = 0;
int shoe_pressure_front_pin = 1;
int shoe_pressure_rear_pin = 2;

// Calibrated before use
int flex_min = 0;
int flex_max = 0;
```

```
int pressure_min = 0;
int pressure_max = 0;

// Updated every loop
int output_flex = 0;
int output_pressure_front = 0;
int output_pressure_rear = 0;


// Set up of WiFi client
void setup() {
  Serial.begin(115200);
  delay(10);

  // Explicitly set the ESP8266 to be a WiFi-client
  WiFi.mode(WIFI_STA);
  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
  }
}


void loop() {

  // read analog values in from the three different sensors
  int shoe_flex = analogRead(shoe_flex_pin);
  int shoe_pressure_front = analogRead(shoe_pressure_front_pin);
  int shoe_pressure_rear = analogRead(shoe_pressure_rear_pin);

  // map max/min to resolution of half a degree
  output_flex = map(shoe_flex, flex_min, flex_max, 0, 720);
  // map max/min to resolution of 1 for a range of 1000
  output_pressure_front = map(shoe_pressure_front, pressure_min, pressure_max, 0, 1000);
  output_pressure_rear = map(shoe_pressure_rear, pressure_min, pressure_max, 0, 1000);

  // Set default connection data - must be initially updated when pairing devices
  WiFiClient client;
  const char * host = "127.0.0.1";
  const int httpPort = 80;

  // If true, connection failed and do not bother trying to send data
  if (!client.connect(host, httpPort)) {
    return;
  }

  // URL to send
  String url = "/data/";
  url += "?flex=";
  url += output_flex;
  url += "&pressure_front=";
  url += output_pressure_front;
  url += "&pressure_rear=";
  url += output_pressure_rear;

  // This will send the request to the server
  client.print(String("GET ") + url + " HTTP/1.1\r\n" +
               "Host: " + host + "\r\n" +
               "Connection: close\r\n\r\n");
  unsigned long timeout = millis();
  while (client.available() == 0) {
    // Maximum time before timeout is 0.1 seconds
    if (millis() - timeout > 100) {
      client.stop();
```

```
      return;
    }
  }
}


// Function to calibrate a sensor
void calibrate_sensor(int pin_sensor_to_calibrate, int type) {

  if (type == 0) {
    // Pressure sensor
    // User put no pressure on sensor for 10 seconds
    delay(5000);
    pressure_min = analogRead(pin_sensor_to_calibrate);
    delay(5000);
    // User put max safe pressure on sensor for 10 seconds
    delay(5000);
    pressure_max = analogRead(pin_sensor_to_calibrate);
    delay(5000);
  } else {
    // Flex sensor
    // User put no flex on sensor for 10 seconds
    delay(5000);
    flex_min = analogRead(pin_sensor_to_calibrate);
    delay(5000);
    // User put max safe flex on sensor for 10 seconds
    delay(5000);
    flex_max = analogRead(pin_sensor_to_calibrate);
    delay(5000);
  }

}
```

Listing 1: Code for shoe sub-system

```
// Code for knee component to device
// This device is programmed via the Arduino IDE
// Reads signals from accelerometer and flex center while simutaneously getting values from
   shoe of 3 sensors
// Computes whether a risky movement has been made for the player

#include <ESP8266WiFi.h>
#include <ESP8266WebServer.h>

// Default password used for network client
const char *ssid = "ssid";
const char *password = "pass";

// Pins for sensors
int knee_flex_pin = 0;
int accel_x_pin = 1;
int accel_y_pin = 2;
int accel_z_pin = 3;

// values from knee
int knee_flex = 0;
int accel_x = 0;
int accel_y = 0;
int accel_z = 0;

// values from shoe
int shoe_flex = 0;
int pressure_front = 0;
int pressure_rear = 0;

```

```
// Calibrated before use - uses same function as shoe sensors
// NOTE: As an accelerometer is harder for the player to calibrate themselves, it will be calibrated
// independently to ensure proper functionality
int flex_min = 0;
int flex_max = 0;

ESP8266WebServer server(80);

// Function to extract variable values
void handleSentVar() {
  // if the request has the three expected values
  if (server.hasArg("flex") && server.hasArg("pressure_front") && server.hasArg("pressure_rear")) {

    shoe_flex = server.arg("flex").toInt();
    pressure_front = server.arg("pressure_front").toInt();
    pressure_rear = server.arg("pressure_rear").toInt();

    server.send(200, "text/html", "Received");
  }
}


// Setting up the server for receiving data from the shoe
void setup() {

  WiFi.softAP(ssid, password);
  IPAddress myIP = WiFi.softAPIP();

  server.on("/data/", HTTP_GET, handleSentVar);
  server.begin();
}


void loop() {
  server.handleClient();
  // get sensor values from accelerometer

  // read flex and accelerometer values
  knee_flex = analogRead(knee_flex_pin);
  accel_x = analogRead(accel_x_pin);
  accel_y = analogRead(accel_y_pin);
  accel_z = analogRead(accel_z_pin);

  // map max/min to resolution of half a degree
  knee_flex = map(knee_flex, flex_min, flex_max, 0, 720);

  // calculate risk - return 0 is safe, 1 if risky
  if (checkrisk(knee_flex, accel_x, accel_y, accel_z, shoe_flex, pressure_front, pressure_rear) == 1) {
    alertTeam();
  }
}
```

Listing 2: Code for knee sub-system

A.3 CAD Model of the Human Knee

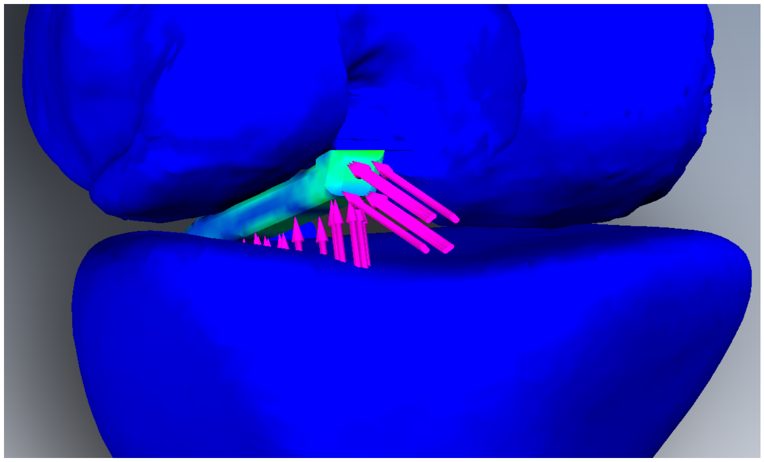

Figure 3: ACL Soild Model under FEA

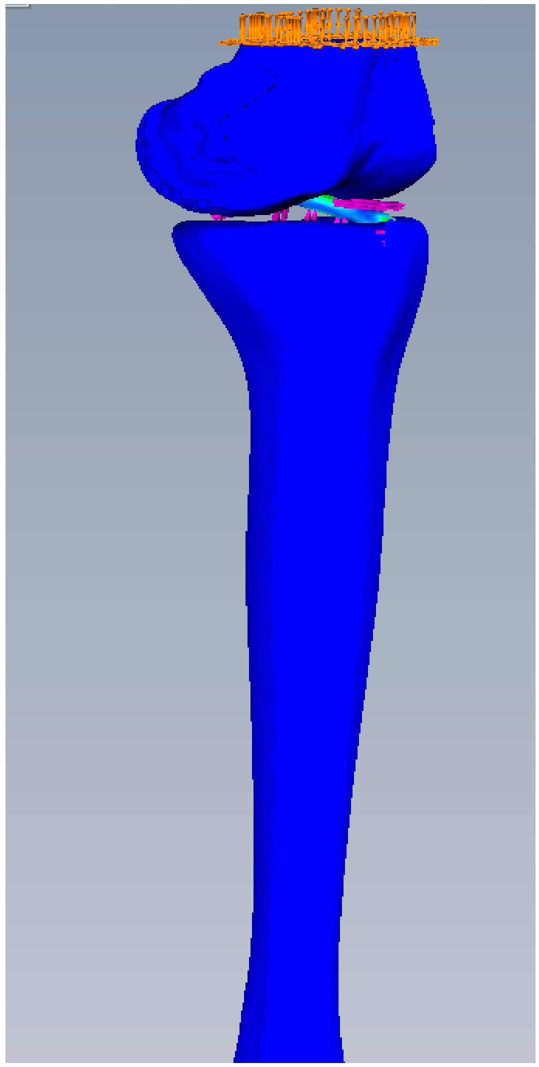

Figure 4: Entire Model used of FEA

Figure 5: Final design of device on athlete's right leg

A.4 Preliminary Circuit Diagrams

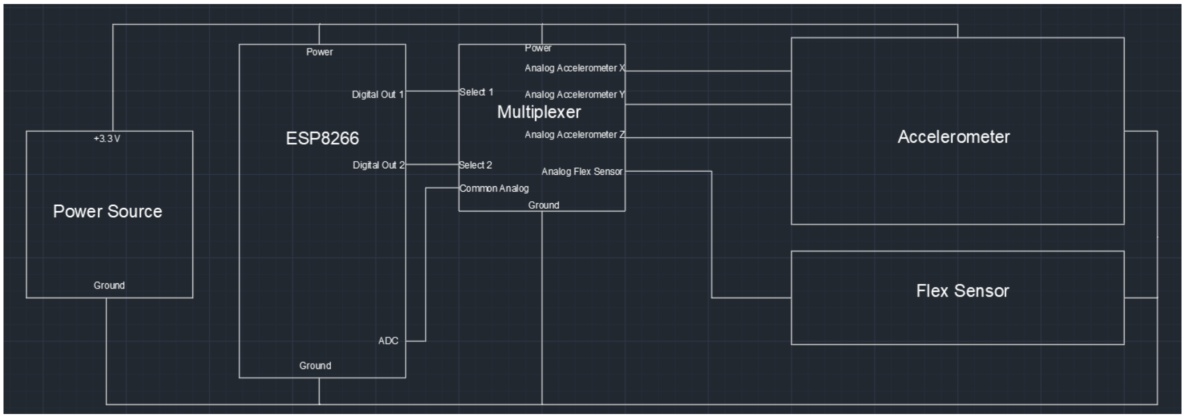

Figure 6: Circuit for knee sub-system

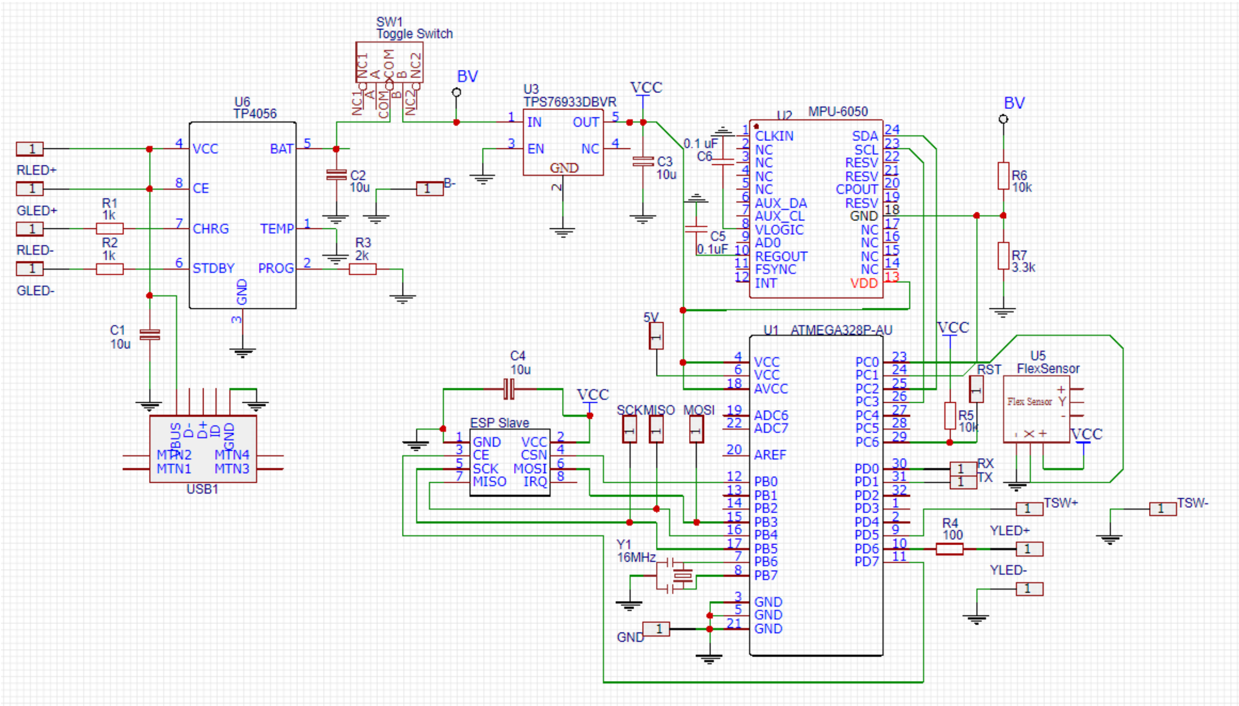

Figure 7: Circuit diagram for the knee sub-system

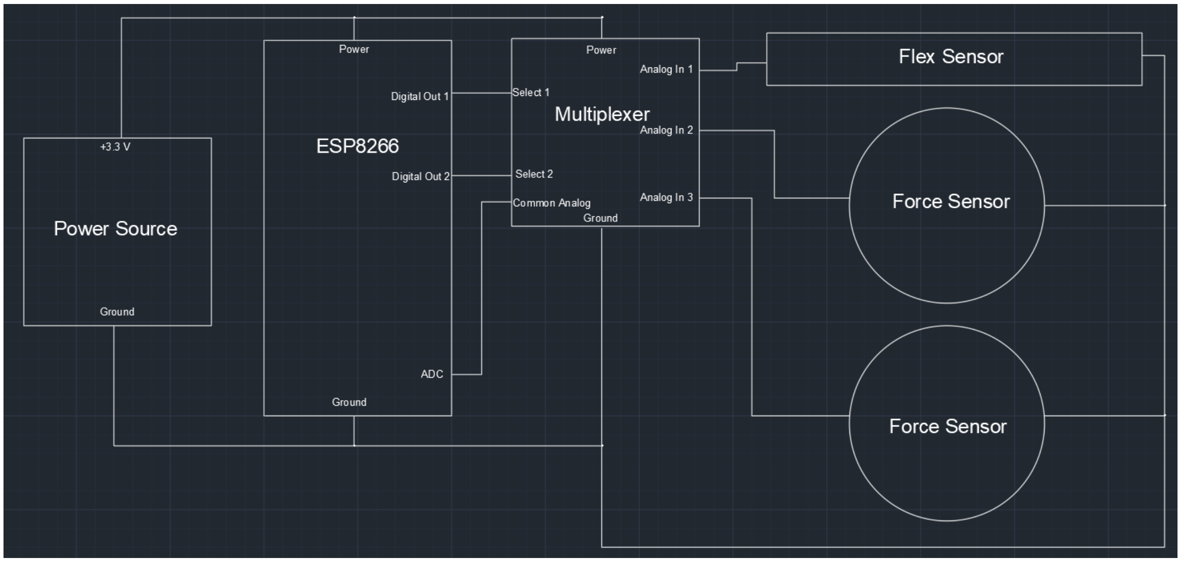

Figure 8: Circuit for shoe sub-system

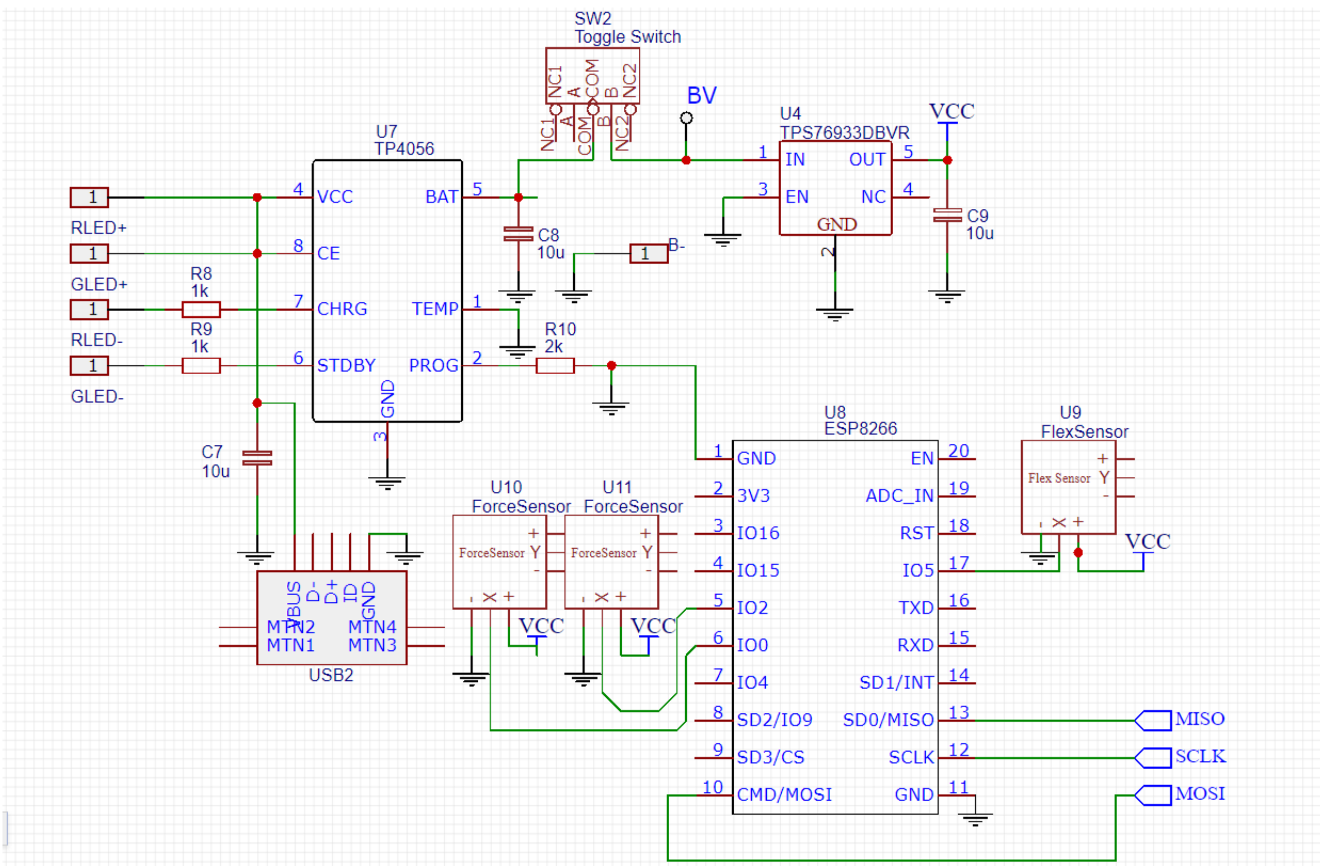

Figure 9: Circuit diagram for shoe sub-system

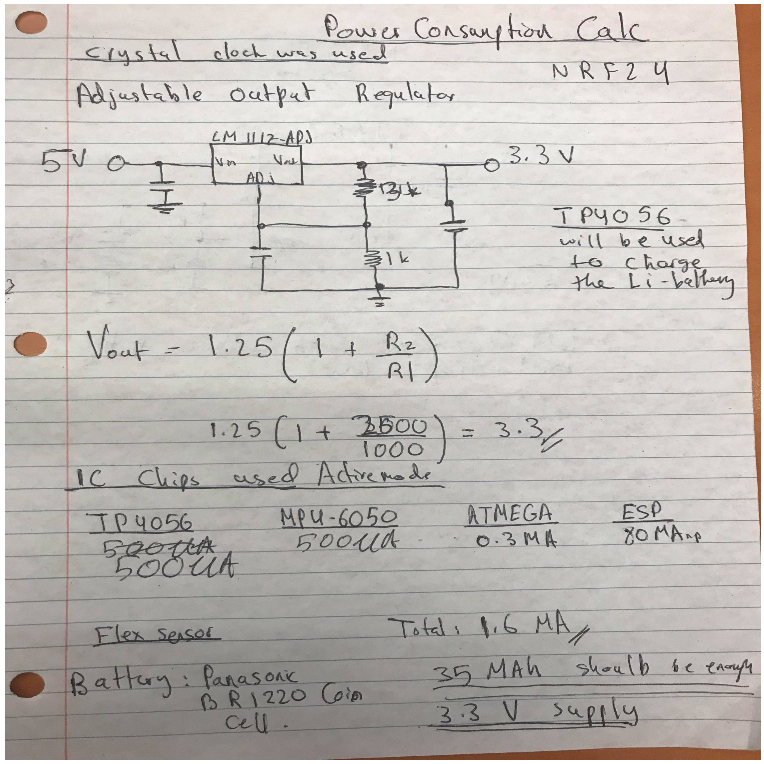

Figure 10: Power consumption calculations

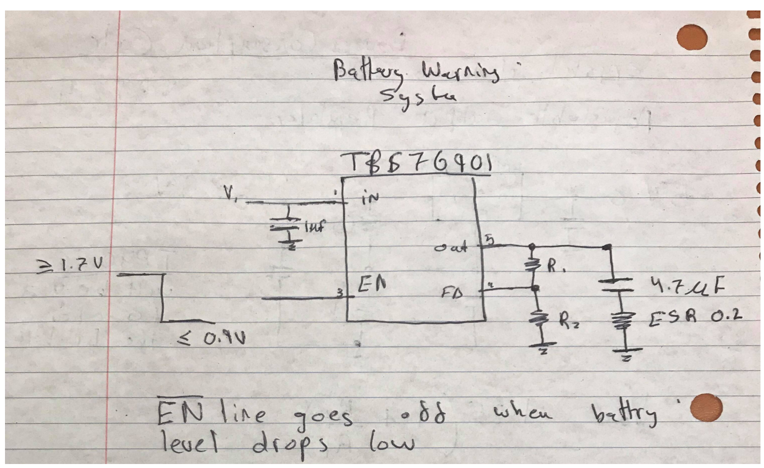

Figure 11: battery warning system