# *System Design of a Knee Motion Sensor to Prevent ACL Injuries*

Taban Yazdani, Anthony Petro, Anas Alharbi, Salima Sekandari

***Abstract—One of the most common traumatic sport-related injuries with potential short and long-term morbidities is the Anterior Cruciate Ligament (ACL) injury. More than 200,000 people sustain ACL injuries each year in the United States alone. Additionally, female NCAA athletes are 2 to 8 times more likely to sustain an ACL injury than male NCAA athletes. ACL injuries occur when the force on the ACL, known as the Tibial Shear Force (TSF), exceeds 2100 Newtons (N). ACL injuries do not heal on their own; therefore, surgery is usually necessary. Surgical treatment can cost on average $16,000 and requires 6 to 9 months of rehabilitation. Athletes cannot feel pain when they are applying an excessive amount of strain on their ACL. As a result, they are unaware of when their TSF approaches 2100 Newtons. A Knee Motion Sensor (KMS) has been developed to provide real-time situational awareness for athletes in a game by: (1) using inputs retrieved from sensors and converting it into usable data (2) using data along with TSF equations to calculate the strain being placed on the ACL (3) alerting the user if the TSF is approaching 2100 Newtons and (4) allowing the athlete to use situational awareness for a post-game analysis on which movements they are doing that may be harming their ACL. Verification testing has been completed to prove that the prototype meets the system requirements. The pressure pads exhibited an accuracy of 89.0% in the range of 2.27 kg to 80.63 kg. The flex sensor measured angles with an accuracy of 96.8% between 35° and 180°.The accelerometer was shown to measure the acceleration with an average error of 0.45 m/s$^2$. Preliminary testing demonstrated that the KMS estimated the TSF within tolerance to provide the athlete with real-time situational awareness in both game-time setting and post-game analysis.***

***Keywords: ACL injuries, knee, knee motion sensor, flexion/ extension injuries***

## I. INTRODUCTION

One of the most common traumatic sport-related injuries with potential short and long-term morbidities is the Anterior Cruciate Ligament (ACL) injury [1]. The number of ACL reconstruction surgeries rose from 87,000 (per 100,000 person-years) in 1994 to almost 130,000 (per 100,000 person-years) in 2006. This rate rose even more rapidly in female athletes compared to their male counterparts. Today, 1 in every 13 women athlete suffer from ACL injury. Landing from a jump incorrectly, sudden stop or deceleration while running or rapid change in direction of knee movement are examples of activities which most of the ACL injuries occur. During these movements, many muscle actions are involved which require various co-contraction strategies to neutralize the high load of force being applied to the knee joint and to stabilize the knee joint[2].

## II. KNEE ANATOMY

There are five major components of the knee: bones, muscles, cartilage, tendons, and ligaments [Fig. 1]. Ligaments connect bones together and strengthen and stabilize the knee. There are 4 ligaments in the knee: Medial Collateral Ligament, Lateral Collateral Ligament (which are on the two sides of the knee attaching the femur to tibia), Anterior Cruciate Ligament, and Posterior Cruciate Ligament, which is located inside the knee joints and attaches the femur to the tibia.

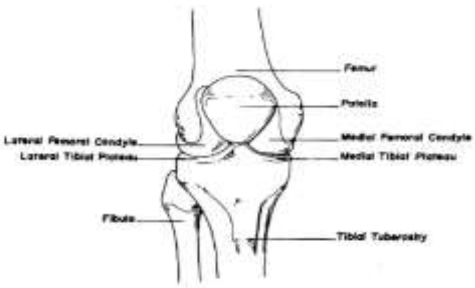



Figure 1: Knee Anatomy

## III. KNEE FORCE

Six different forces are applied to the knee 1) foot force($F_f$)2) shank force($F_{sh}$)3) ground reaction force($F_{GR}$) 4) hamstring ($F_h$) 5) quadriceps($F_H$) and 6) gastrocnemius force($F_G$). The sum of all the forces being applied to the knee is equal to "Tibial Shear Force". Tibial shear force (TSF) is the force which applies to the ACL and causes that ligament to tear. Understanding TSF is necessary for a system to provide situational awareness for athletes and prevent ACL injuries[3]. The angle between the y or x axis of earth and the y or x axis of shank is called the shank angle($\square_{sh}$ )[Fig. 2]. Additionally, in the equation of muscles the angle used is called the "Flex angle" which is the angle between the femur and tibia [Fig. 3].

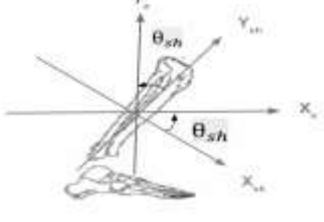


Figure 2.

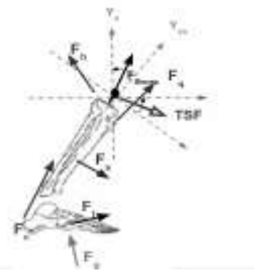



Figure 3.

$$TSF = F(Shank) + F(Foot) + F(Ground\ Reaction) + F(Muscles)$$

$$TSF = m_{sh}\,[a_{sh\,X}\cos(\theta_{Sh}) - (a_{sh\,Y} + g)\sin(\theta_{Sh})] + m_f[a_{f\,X}\cos(\theta_{Sh}) - (a_{f\,Y} + g)\sin(\theta_{Sh})] - F_{GRx}\cos(\theta_{Sh}) + F_{GRy}\sin(\theta_{Sh}) - \Sigma F(Gastro) - \Sigma F(Quad) - \Sigma F(Ham)$$

$$F(Quad) = F(Quad)\sin((-0.238)*(180 - flexB) + 22.2)$$

$$F(Ham) = F(Ham)*\cos(90 - flexB)$$

$$F(gastro)=F(gastro*\sin(\sin-1((d*\sin(flexB))/(d2+ \quad tibia(length)2 \quad - 2*d* tibia(length)*\cos(flexB))-2))$$

## V. FAILURE MECHANISMS

ACL tears can be classified into two categories: contact and non-contact. These constitute 30% and 70% of all ACL injuries, respectively. Contact injuries generally occur when an athlete comes into sudden contact with another player. They are composed of distraction/compression, lateral/medial, and posterior/anterior injuries. Distraction/compression injuries occur when the shank and femur are either pulled apart or shoved together. Lateral/medial injuries occur when the shank makes a horizontal translation to the side. Finally, posterior/anterior injuries occur when the shank translates either behind the femur or in front of the femur towards the right. Non-contact ACL injuries are broken down into three types of failure mechanisms and two combinations: internal/external, abduction/adduction, flexion/extension, internal/external rotation with abduction/adduction, and internal/external rotation with flexion/extension. These constitute approximately 16%, 9%, 37%, 1%, and 37% of non-contact ACL injuries, respectively.

## XIII. TEAM CONTRIBUTION

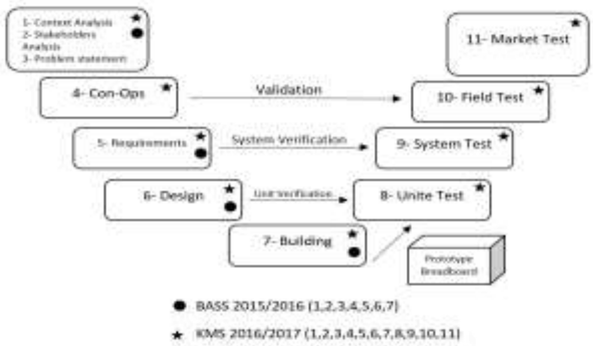



Figure 4: Team Contribution

The work that KMS has completed from 2016 to 2017 is built on the foundational work done by the BASS team from 2015 to 2016 [2]. The BASS prototype included one sensor on a standard Arduino board and completed steps 1-7 in [Fig. 4].

## IV. PROBLEM STATEMENT

Despite the large number of studies being done on identifying ACL injuries and its failure mechanisms, 1 out of 13 female NCAA athletes still sustain an ACL injury. Of these injuries, flexion/extension injuries account are most common, with a total of 37% of non-contact ACL injuries falling into this category. Currently, no system exists for quantifying the strain on the ACL in order to prevent ACL injuries from occurring to athletes.

## VII. CONCEPT OF OPERATION (CONOPS)

One way to prevent and minimize ACL injuries is to create and implement a wearable knee motion device composed of five sensors: one accelerometer, two pressure pads, and two flex sensors. This knee motion sensor (KMS) actively quantifies the TSF and provides real-time situational awareness for the athlete in a game by:

- Use inputs retrieved from sensors and converting it into usable data
- Use the data and tibial shear force equations to determine the amount of strain being placed on the ACL
- Once the risk of the strain being placed is determined, the system alerts the user of an elevated risk
- Situational awareness can be used in post-game analysis to see which movements done by athletes may be causing harm to their ACL

## VIII. DESIGN

### *A. Functional Description*

The knee motion sensor receives multiple inputs. Inputs include:

- User inputed height and weight to estimate the mass and length of the shank and the foot
- Sensory inputs of the shanks linear acceleration in the x, y, and z axis
- Shank and flex angles
- Heel and ball pressures of the foot

The inputs are used in the arduino TSF equation to estimate the tibial shear force and wirelessly transferred to a matlab interface to graphically display and archive the data for future review. The estimated TSF would be compared with the threshold of 2050 Newtons. If the estimated TSF exceeds the threshold, the device is going to alert the user via haptic, visual, and audible alerts.

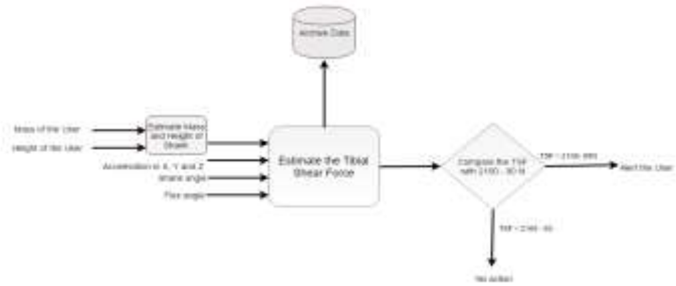



Figure 5: Functional Description Diagram

### *B. Design Components*

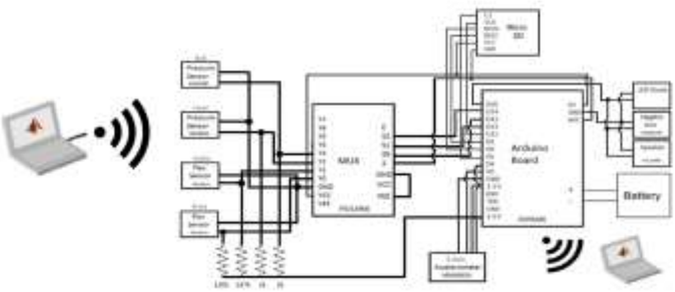
The components incorporated into the design are the following:

- 1 three-axis accelerometer, for measuring the linear acceleration and rotations of the shank through the different gait phases
- 2 flex sensors, one on the front of the knee, over the patella, and one on the front of the ankle to measure the angle between the femur and shank, as well as the angle between the shank and the foot
- 2 pressure pads on the underside of the foot: one under the ball and one under the heel. This ensures that loading phases of the foot and work in conjunction with the derived angles and linear acceleration of the shank in order to measure the ground reaction forces exerted on the foot through the phases of the user's gait.

Each component was selected to specifically address a certain role in calculating the TSF. Please reference Table 2 which displays the sensors along with their corresponding role in the TSF equation.

| Terms in TSF | Sensor | Model Number |
|---|---|---|
| Shank acceleration | Accelerometer | MMA845A |
| Shank angle | Flex Sensor | F5-6512 |
| Flex angle | Flex Sensor | F5-6512 |
| Foot Force | Pressure Pad | B005CBC |
| Ground Reaction | Pressure Pad+ Accelerometer | B005CBC+MMA845A |

Table 1: Sensors for TSF Equation




*C. Circuit Component Description*

The circuit diagram for the prototype is shown in Figure 5. The system inputs are all the components leading into the left side of the arduino board. A multiplexer selects one of several analog or digital input signals and forwards the selected input into a single line. This is used in order to facilitate the use of multiple sensors on one arduino board. The corresponding analog voltages are then received by the microcontroller's Analog to Digital Converter(ADC) pin where they are converted to a digital number. The linear acceleration values of a 3-axis accelerometer are then combined with the multiplexor inputs, converted to corresponding usable values, and finally introduced into the TSF equation to compute the Tibial Shear Force and compare it against the threshold of 2050N. In the event that the TSF threshold is exceeded it alerts the user through audible beep, visual flash of an LED, and a haptic disc. The data is then wirelessly transferred to the a matlab interface where it is graphically displayed and archived for postgame analysis. Figure 6: Circuit Component Diagram

## IX. PRODUCT TESTING

In order to successfully test the product, each test had to be calibrated and test each component individually before combining them all. The testing was decomposed into four main phases which can be seen below:

| Description | Test Case | Objective |
|---|---|---|
| 1. Pressure Sensor | 1.1 Pressure Sensor Calibration<br>1.2 Bent Leg Test<br>1.3 Straight Leg Test<br>1.4 Placing Weights Test | Validate the pressure sensor data by comparing the output data of the pressure pad used in Arduino with the measured pressure using a digital scale. |
| 2. Flex Sensor (Knee and Ankle) | 2.1 Ankle Sensor Calibration<br>2.2 Knee Sensor Calibration<br>2.3 Electronic Goniometer vs Flex Sensor Test | Test the accuracy of the angle measurements of the Arduino Device |
| 3.Accelerometer | 3.1 Accelerometer Calibration<br>3.2 Bent Leg Test<br>3.3 Straight Leg Test<br>3.4 Dropping Block Test | Test the accuracy of the acceleration measurements of the Arduino Device |

Table 2: Test Phases Description, Test Case, and Objective

*1. Pressure Sensor*

The two pressure pads were each calibrated and tested multiple times for each set of weights in four different stages.

*1.1 Pressure Sensor Calibration*

The pressure sensors were calibrated by placing a 40 lb weight (minimum) and a 260 lb weight (maximum) on the pressure sensor and recording the arduino value. The minimum was then subtracted from the maximum to get the range. This was done for 330, 1k, 2k, 5k, and 10k resistors. These resistors had the following corresponding ranges: 561, 649, 64, and 12 respectively. The 2k resistor was chosen because it provided the largest range of 649 [Table 4].

*1.2 Bent Leg Test*

A bent leg test was conducted to record the shifting in weight between the heel and toes of the foot while landing. This test was done by placing two pressure pads, one under the toes, and one under the heel. The test subject then stood on a 30 cm tall stool and performed a bent leg jump and landed 8 cm in front of the stool. This was done for 20 trials and the data was recorded. Below is an example of the data of the pressure pads for one of the bent leg jumps, as shown in Figure 7 at point (a) the pressure for both toes and heels are zero, which shows the person is in the air and at point (b) the person just landed on the ground, which in this example the person landed on toes first (a).


Figure 7 : Bent Leg Jump Pressure Pad Data

*1.3 Straight Leg Test*

A straight leg test was conducted in order to compare to the bent leg test in regards to shifting in weight between the toes and heel. This test was done similar to the bent leg test; however, rather than the individual performing a bent leg jump, they performed a straight leg jump. Below (Figure 8) is an example of the data of the pressure pads for one of the straight leg jumps. At point (a) the pressure for both toes and heels are zero, which shows the person is in the air and at point (b) the person just landed on the ground which in this example the person landed on toes and heels at the same time (a).

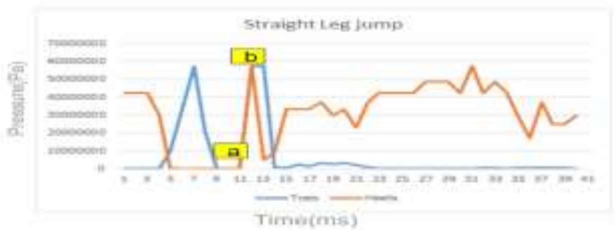



Figure 8 : Straight Leg Jump Pressure Pad Data

*1.4 Placing Weights Test*

In order to validate the pressure sensors at a wide variety of weight ranges, weights ranging from 40 lbs to 260 lbs were placed on the pressure sensors and the raw arduino output value was recorded. The actual pressure in Pascals for each weight was calculated by using the equation P = F/A. The actual pressure value was graphed against each arduino value, and the equation for the best fitted line was found. This proved to be a power equation of $y = 6E + 08x^{-1.207}$ with a $R^2$ value of 0.9059. This equation was then used to convert the raw Arduino value to Pascals in order to compare it with the actual pressure value. The converted Arduino value was compared to the pressure pad measurements and the actual pressure to determine the accuracy of the pressure pads.

*1.5 Pressure Pad Test Results*

In Table 5, a summary of some of the values for the Arduino pressure, calculated pressure, actual pressure, and percent error for each weight can be seen. The average percent error for the pressure pads between all the weights is 14%.

| Weight(lb) | Arduino Value | Calculated Pressure | Actual Pressure | Percent Error |
|---|---|---|---|---|
| 40 | 901.58 | 162727.54 | 156064.6 | 4.27% |
| 80 | 455.25 | 371221.43 | 312129.3 | 18.93% |
| 120 | 375.99 | 467141.92 | 468193.8 | 0.12% |
| 160 | 314.52 | 580093.09 | 624258.5 | 7.07% |
| 220 | 272.80 | 688793.57 | 858355.1 | 19.7% |
| 260 | 252.26 | 757028.75 | 1014419.6 | 25.37% |

Table 4. Pressure Sensor Data

*2.0 Flex Sensor*

The two flex sensors were calibrated individually, one for the ankle and one for the knee. This was done because the ankle and knee have different ranges in which they can bend.

*2.1 Ankle Sensor Calibration*

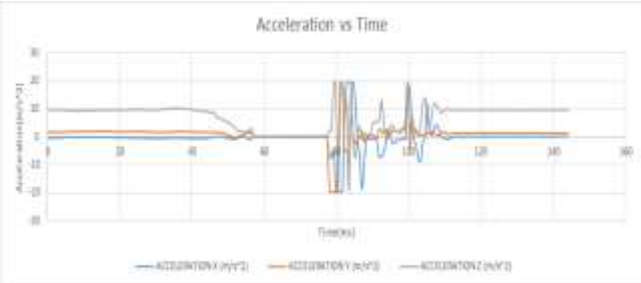
The ankle flex sensor was calibrated by aligning it with a goniometer. The goniometer, with the flex sensor attached, was then moved to 160 degrees (minimum flex) and the flex sensor value was recorded. This was also done for 97 degrees (maximum flex). The minimum arduino value was subtracted from the maximum to get the range. This was done resistors of the following values: 100k, 110k, 120k, 137.5k, 147k, 157.5k, 200k, and 220k resistors. Resistor values of ≤ 100k and ≥ 220k were out of range, while the ranges of the remaining follow: 24, 439, 450, 475, 338, 239, and out of range, respectively. The 147k resistor was chosen given that it provided the largest range of 475.

*2.2 Knee Sensor Calibration*

The Knee Flex Sensor (KFS) was calibrated by aligning it with a goniometer. The goniometer, with the flex sensor attached, was set to 180 degrees (minimum flex) and the flex sensor value was recorded. This was also done for 25 degrees (maximum flex). The minimum was subtracted from the maximum to get the range. This was done for 110k, 120k, 135k, 145k, and >= 150k resistors. These resistors had ranges of 307, 437, 323, 300, and out of range, respectively. The 120k resistor was chosen given that it provided the largest range of 437.

*2.3 Electronic Goniometer vs. Flex Sensor Test*

In order to further validate the flex sensor for the KMS device, it was tested against the goniometer to determine the accuracy. The flex sensor was aligned with the goniometer and moved from 25 degrees to 180 degrees in 5 degree increments with the flex sensor value recorded at each. These values were then




graphed against the actual degrees given by the goniometer in order to find an equation to convert the pressure pad values to degrees. This had to be done for both the ankle and knee flex sensors individually. The equation for the ankle flex sensor was linear, being $y = -0.1736x + 269.93$with an $R^2$of 0.94122. The equation for the knee flex sensor was linear as well, being $y = -0.2258x + 335.35$with an $R^2$of 0.92141.

*2.4 Flex Sensor Test Results*

The actual degree, arduino degree, calculated degree, error, and percent error are all shown in Table 8 and Table 9, for the ankle and knee flex sensors respectively.

| Ankle | | | | |
|---|---|---|---|---|
| Actual Degree | Arduino Degree | Calculated Degree | Error | Percent Error |
| 110.00 | 903.77 | 113.03 | -3.03 | 2.76% |
| 120.00 | 889.17 | 115.57 | 4.43 | 3.69% |
| 130.00 | 813.00 | 128.79 | 1.21 | 0.93% |
| 140.00 | 746.74 | 140.30 | -0.30 | 0.21% |
| 150.00 | 620.12 | 162.28 | -12.28 | 8.19% |
| 160.00 | 630.29 | 160.51 | -0.51 | 0.32% |
| 170.00 | 592.48 | 167.08 | 2.92 | 1.72% |
| 180.00 | 561.50 | 172.45 | 7.55 | 4.19% |
| | | | Average: | 2.75% |

Table 5: Ankle Flex Sensor Data

| Knee | | | | |
|---|---|---|---|---|
| Actual Degree | Arduino Degree | Calculated Degree | Error | Percent Error |
| 110.00 | 941.72 | 122.71 | -12.71 | 11.56% |
| 120.00 | 959.40 | 118.72 | 1.28 | 1.07% |
| 130.00 | 945.01 | 121.97 | 8.03 | 6.18% |
| 140.00 | 883.50 | 135.86 | 4.14 | 2.96% |
| 150.00 | 811.25 | 152.17 | -2.17 | 1.45% |
| 160.00 | 755.57 | 164.74 | -4.74 | 2.96% |
| 170.00 | 765.47 | 162.51 | 7.49 | 4.41% |
| 180.00 | 682.08 | 181.34 | -1.34 | 0.74% |
| | | | Average: | 3.92% |

Table 6: Knee Flex Sensor Data

3.0 Accelerometer

The 3-axis accelerometer was tested in three phases: accelerometer calibration, bent leg test, and straight leg test.

*3.1 Accelerometer Calibration*

The testing began by gathering baseline data used to compare the results from each successor to its predecessor. The experiment began by a collection of baseline data through conducting drop tests with the Android mobile application, AndroSensor, in order to gather baseline linear acceleration data of the wearers shank in the x, y, and z-axis with a sampling rate of 5 ms within Y seconds.

Figure 9: Accelerometer vs Androsensor

*3.2 Bent Leg Test*

Data was gathered for the baseline drop by attaching the Android device running AndroSense application to a block and dropped it from 30 cm. Then data was collected from 5 users, each conducting 5 bent leg tests from a height of 30 cm wearing the android device on the inner portion of the upper shank and recorded the data. Next, the experiment repeated the same procedure but with an accelerometer attached to the individual's inner portion of the upper shank and recorded that data to compare to the AndroSensor.

*3.3 Straight Leg Test*

An experiment was conducted with straight leg test following the same procedure; however, rather than the individual performing a bent leg jump, they performed a straight leg jump. This was done to see if there were any changes in acceleration between a straight and bent leg jump.

*3.4 Dropping Block Test*

Testing compared the results from each successor to its predecessor. The experiment began by a collection of baseline data through conducting drop tests with the Android mobile application, AndroSensor, in order to gather baseline linear acceleration data of the wearers shank in the x, y, and z-axis. This baseline data was paired with slow motion video capture during each test.

### *3.5 Accelerometer Test Results*

In order to calculate the accuracy of the accelerometer, the accelerometer and the phone were placed (with the AndroSensor app) on a 6 lb weight block at the same time. The block was then dropped from a 30 cm height in order to record the acceleration in the x, y, and z directions. The results between the arduino readings and the app were compared [Table 10]. The percent error for the accelerations in the x, y, and z directions were 0.0282, 1.233, and -0.11 ($m/s^2$), respectively

| | X Acceleration (m/s^2) | Y Acceleration (m/s^2) | Z Acceleration (m/s^2) |
|---|---|---|---|
| Calculated Acceleration | 0 | 0 | 9.8066 |
| Arduino Acceleration Average | -0.0282 | 1.2330 | 9.6907 |
| Standard Deviation | 0.3708 | 0.1321 | 0.2192 |
| Error | 0.0282 | 1.233 | -0.11 |
| Number of trials | 5 | 5 | 5 |

Table 7: Accelerometer Calibration

## XI. BUSINESS CASE

### *A. Market Opportunity*

Based on the context mentioned earlier, two main categories of customers were identified which would benefit from using Knee Motion Sensor. The first category is athletes, including NCAA students, youth athletes, recreational athletes and professional athletes which play in leagues with a total number of 50 million people. The second category, which includes more than 300,000 people, includes any individuals who previously have experienced any kind of knee injuries, such as knee joint (meniscus) ligament tear, posterior cruciate ligament (PLC) and of course, the most common, ACL injury.

### *B. Revenue and Cost Analysis*

The project cost can be divided into two categories: start up cost and operational cost. The process of both costs includes recurring and nonrecurring costs. The total cost of building the device is $180 and the startup cost of the first year of operation, including variable cost and overhead cost, is $650,000. Based on the potential market of 50 million individuals and the market value of $1000 for the KMS device, two scenarios were considered: optimistic and pessimistic. The optimistic scenario includes an expected market share of 30% with a penetration rate of 8%, which yields a total net value (NPV) of $26,964,307 and a rate of investment (ROI) of 89%. The pessimistic scenario was given a market share of 10% and penetration rate of 5%, yielding an NPV of $16,464,115 and an ROI of 73%. This information is shown in Table 13.

## XII. CONCLUSION

The Knee Motion Sensor (KMS) device has been shown to reduce the risk of sustaining an ACL injury. The knee motion sensor will alert the athlete of an elevated risk and provide them with situational awareness to help mitigate the probability of an ACL injury. Furthermore, the knee motion sensor provides the athlete with real-time situational awareness which they can then use for post-game analysis to see what isolated movements they are doing that may be harmful to their ACL. Based on the requirements, the arduino board included two pressure sensors with an accuracy of 86.0% in the range of 20 kg to 120 kg, two angle sensors with an accuracy of 94.8% between 35° and 180° and a three-axis accelerometer with an error of 0.45 $m/s^2$. Preliminary validation testing demonstrates that the KMS device can provide real-time situational awareness for an athlete in a game and can be used for post-game analysis[Fig.10].

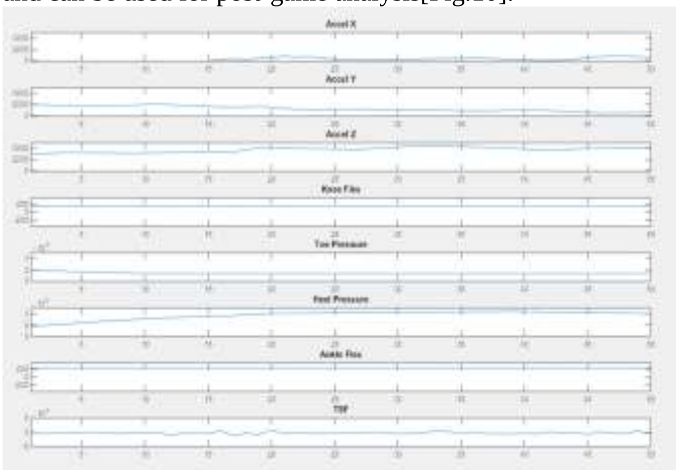


Figure 10: Matlab Graphical Interface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