Knee Joint Data Logging for Gait Analysis

Maxwell Sotnick

California Polytechnic University, San Luis Obispo
max.sotnick@gmail.com

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Abstract

The goal of this paper is to document the design process and results of the system developed to aid in the Gait analysis of the exoskeleton suit. Through the use of a load cell configured around the patella, and a flex sensor along the interior of the knee joint, the main CPU should be able to perform a predictive analysis with regards to the Gait of the user. The primary objectives of this project include the collection of two types of knee data and the data logging of said metrics. By plotting the data with respect to time (normalized as the percent Gait) I have proven the functionality of the design presented. Furthermore, from the results it is evident that both sensors have distinct phases which lends well to the Gait analysis being conducted.

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I. Introduction

The primary goal of the Sensor & Data Collection Team of the Cybathlon Controls division, is to explore, experiment, and develop electrical systems that can be used to collect data for the primary controller to analyze. The data collected spans a wide variety of metrics from positional to strain. With the collected data, the primary controller can determine the current phase within the Gait cycle which the exoskeleton is in. While there are a variety of options to pursue in collecting Gait data, the solution that this team went forward with was to analyze the strain around the patella and knee flexion angle.

Using the knee as a reference point for Gait analysis is a common practice in exoskeleton development. Moreover, monitoring the knee flexion angle is a relatively reliable way in determining the current phase in Gait, while utilizing knee strain and acceleration data can help mitigate the magnitude of error in the resulting analysis [1,2,3]. Since the exoskeleton will utilize an IMU for positional information with regards to the center of mass, I elected to focus on the goniometer and strain detection.

Another goal of this project was to develop a data collection system to access data in the short term for ATM (at the moment) analysis, and in the long term for future inspection of rig efficiency/performance. For the scope of this project, I chose to use a microSD card to store the data long term.

I.I Background

The sensors used to analyze the knee were a two-inch flex sensor (acting as goniometer) and four 350Ω strain gauges in a Full-Bridge configuration. Both sensors are variable resistors which increase in resistance as they are mechanically flexed/contorted. Being the simpler of the two, the flex sensor can be used to determine the angle of flexion based on the change of its resistance. As the knee bends, the resistance of the flex sensor increases linearly with the angle of deflection. Given this predictable operation, the flex sensor can simply be placed in voltage divider with a static resistance—allowing us to easily monitor the flexion angle of the knee.

The latter sensor is essentially a load cell which is being used to determine the amount of strain surrounding the patella. As the knee goes through the gait cycle, the patella experiences varying levels of strain, creating a variable which can be used to determine the current phase in Gait. By placing the variable resistors that strain gauges are into a Wheatstone bridge, the difference in strain experienced by each gauge can be measured and used to determine the current strain experienced by the specimen which the gauges are fixed to. Moreover, different bridge topologies have different benefits. In the case of the Full-Bridge topology, the benefits are as follows [4]:

1. Separation of normal and bending strain (only the bending effect is measured)
2. High output signal and excellent common mode rejection (CMR)
3. Temperature effects are well compensated

Since temperature given off by the human body can effect the results of the strain gauges, the addition of temperature compensation is desirable. Furthermore, the separation of types of strain will allow for the data to be more narrowed in scope, minimizing the amount of noise seen. While the Full-Bridge configuration gives has a strong signal quality, the sensor will still require an amplifier of some sort so that the signal can be read by the microcontroller.

II. Methodology

As outlined in the introduction, the goal of this project was to collect the flexion angle data given by the flex sensor, and the strain data of the patella. The flex sensor would be placed on the inside of the knee joint, while the strain gauges would be evenly spaced around the circumference of the patella. Holding the sensors in place is a flexible knee brace with a patella cushion in order to maximize the contact between both the knee and the sensors. By having a tight fitting brace,Ican ensure that the strain imparted on the patella would be detected by the strain gauges. The placement of components with

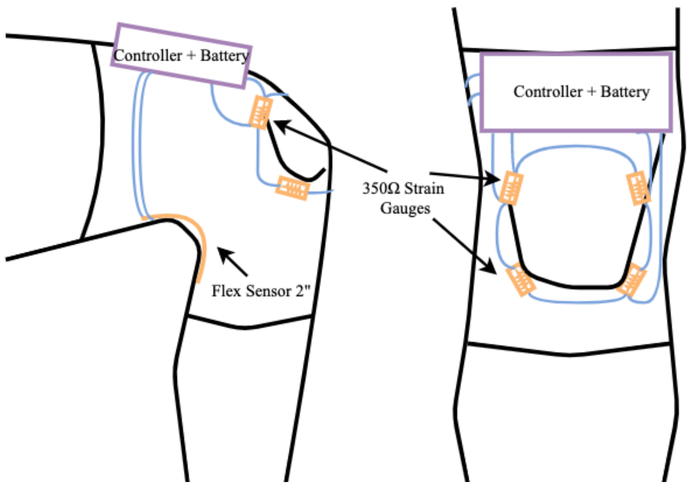

Fig 1. Technical illustration of sensors and electronics placement on knee

respect to the knee is shown in Figure 1. Given that the primary concern was the acquisition and maintenance of data,Iplaced less of a priority on the overall compactness and form factor of the associated electronics. However, it was important to consider the weight of the controller and battery since it could impact the sensor-to-skin contact. Additionally, the added weight could effect the material of the brace, creating strain on the sensors which is not reflective of the forces imparted on the knee.

With regards to the electronics, the circuitry can be broken down into five sub-circuits: MicroSD Breakout, Full-Bridge Connection, Load Cell Amplification, Flex Sensor Connection, and Battery/Power-In Management. The complete circuit shown in Figure 2 is what was used in testing and closely resembles the final circuit which was implemented as a PCB. The power source for this circuit will ultimately be supplied through a lower voltage rail connected to the main electronics battery. Given this, the power circuitry used here is purely meant for testing and is not present in the PCB design. Additionally, several of the logic-level conversions seen here are not present in the final PCB design as well, since it was decided to operate the final subsystem at a lower voltage—3.3 V. Decreasing the voltage does not seem to impact the accuracy and precision of readings, and instead may prove to be more power efficient.

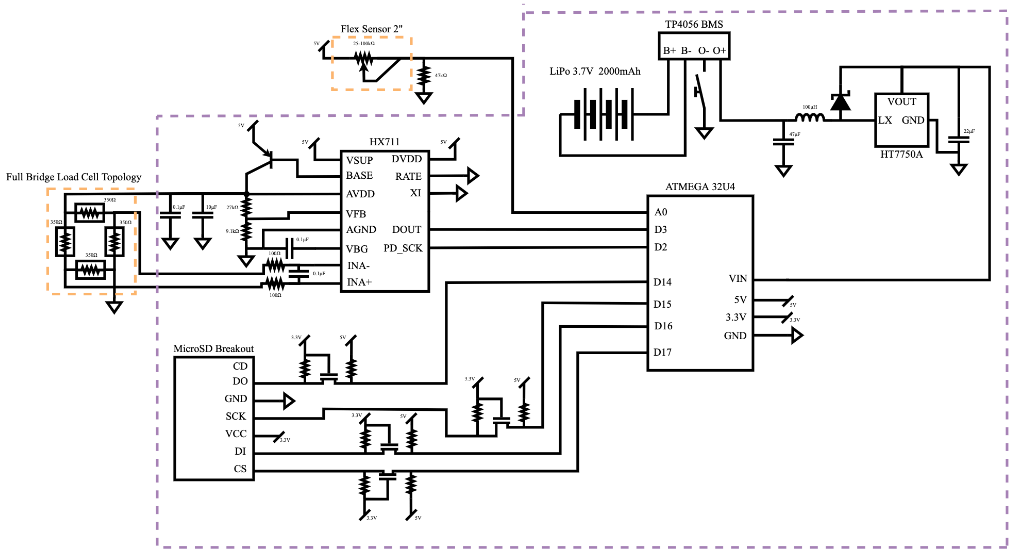

Fig 2. Complete circuit diagram; Note that the circuit depicted here utilizes a 5V logic-level

II.I MicroSD Breakout

Interfacing with a microSD card is relatively straightforward asIcan simply use the SPI protocol to write and read. The notable piece of design is the use of P-type MOSFETs to avoid an over voltage of on the microSD pins. Since microSD cards operate between 2.7-3.6 V the 5 V logic-level of the microcontroller needs to be converted into a lower, acceptable logic-level. Utilizing the 3.3 V rail of the microcontroller, the digital signals could be easily converted into a logic-level within the microSD's operational range. The use of logic-level shifters on the microSD data lines is unneeded in the PCB design since the microprocessor is operating at 3.3 V instead of 5 V.

II.II Full-Bridge Connection

As stated in the introduction, there are several topologies used for creating a load cell from strain gauges. For the purposes of this project, the use of a full-bridge topology lends itself best to the gauge's placement on the specimen (the knee). Moreover, the data collected from this configuration is reflective of the strain data needed to properly asses the Gait of the user. Listed as a benefit of this topology, the output signal is relatively high for, however still requires amplification in order to be read by the microcontroller. The nominal resistance of the strain gauges is 350 Ω, which is among the standard gauge ratings.

II.III Load Cell Amplification

For the load cell amplifier I used the HX711 24-bit ADC which utilizes a low-noise PGA. The connections and topology closely match the typical application shown in the corresponding data sheet [5]. Being relatively straightforward implementation, there were two main design considerations: data rate, and the resistances seen on the VFB pin. The HX711 IC has a RATE pin which allows the user to toggle between an output data rate of 10 and 80 Hz. By grounding the pin, I fix the data rate to 10 Hz. While this caps the operation of the load cell at a slower speed, it also reduces the amount of noise added to each measurement. Since the Gait analysis requires the collected data to be fairly consistent, the tradeoff between speed and precision is acceptable. The second design decision was what size resistors to use on the VFB pin. Given that the data sheet gives the nominal regulator current (1400 μA), the desired values can be easily calculated as a voltage divider:

$$5V = V_{FB}\left(\frac{27k\Omega + 9.1k\Omega}{9.1k\Omega}\right) \rightarrow V_{FB} = 1.26V$$

$$I_{Reg} = \frac{5V - 1.26V}{27k\Omega} \approx 0.135\ mA\ \checkmark$$

II.IV Flex Sensor Connection

There are several ways to interface with a flex sensor—the simplest being a voltage divider connected to an analog-in pin. By measuring the change in voltage between both the static resistor and flex sensor, we can get a fairly accurate depiction of how much the knee is bending. The choice in size for the static resistor came down to some tuning in order to find the optimal static resistance for when the flex sensor is at rest.

II.V Battery/Power-In Management

The goal with this sub circuit was to develop a way of managing power into this sensor scheme. In the case that there needed to be a change in supply voltage or a separate battery to power the sensors, the circuitry needed would already be in place. The power system is comprised of a BMS module and voltage booster circuit. Using the HT7750A PFM step-up DC/DC converter, I increased the 3.7V supplied by the battery to 5V. The circuit shown is a standard configuration recommended by the manufacturer given the application [6].

II.VI Data Logging

Aside from the analog circuitry, the other key feature of this project was logging the data for both short and long term use. The crux of the logging system is a struct which contains flex and strain data given a point in time. Given that the possible range of values for the flex sensor is between 0-70 degrees, I only need 1 byte to save this reading. Similarly, the possible range of values for the strain sensor is between 0-2000 grams, meaning that I only need 2 bytes to save the strain data. As for the time, since I want to record the data with an accuracy in milliseconds, 4 bytes should allot more than enough room to support a lengthy runtime. From this struct I are able to keep related data together when writing to the microSD card and export data in the short term for the Gait analysis.

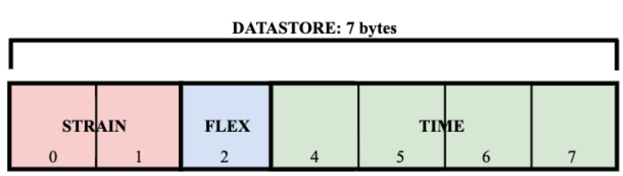

Fig 3. Visual representation of datastore struct

The struct and array are instantiated as follows:

```
struct datastore{
    uint16_t strain;
    uint8_t flex;
    uint32_t time;
};

struct datastore gaitStore[n];
```

Then in the main loop of the program, the following code shows the writing of data on to both serial ports (sdStore and gaitRead):

```
sdStore.write((const uint8_t *)&dataChunk, sizeof(dataChunk));

gaitStore[index]=(const uint8_t *)&dataChunk;
if(index==gaitSize){
    for(i=0;i<gaitSize;i++)
        gaitRead.write(gaitStore[index]);
    index=0;
}else{
    index++;
}
```

Below in Figure 4 is the process flow diagram for the program used:

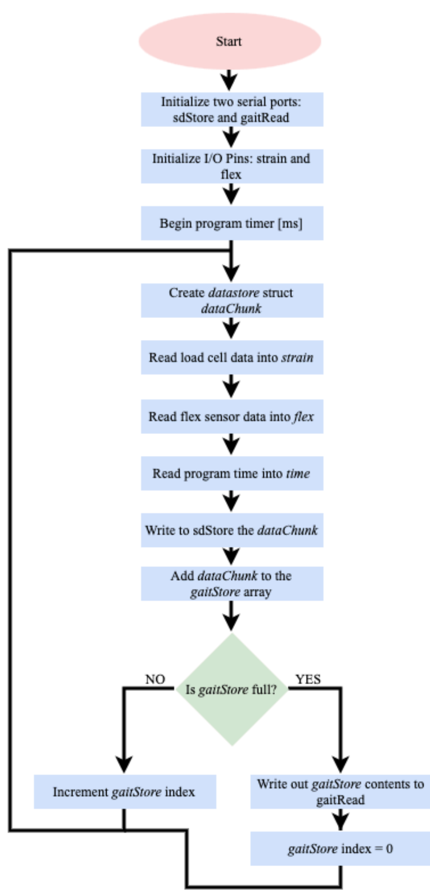

Fig 4. Process flow diagram of program

III. Results

From the work done in the methodology, I tested the system by taking the data with respects to program runtime. Given the recorded datapoints, I plotted the data with respect to the time normalized as phases of the Gait cycle (which is given by the percent of the Gait cycle). This method of plotting Gait data is quite common as it easily shows the correlation between data and the stages of walking. The following diagram is an example of how the Gait cycle is broken down into phases [7]:

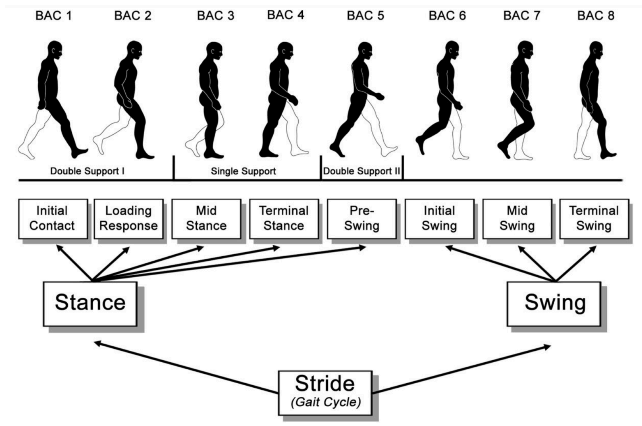

Fig 5. Mental representation of the human gait

From our results it is evident that the sensors have detected clear, distinct phases of the Gait Cycle. Moreover, by using both metrics in conjunction, the main CPU could make a predictive analysis given the trend of realtime data. This is based upon the way in which the data follows a relatively similar pattern—as visualized in the 10 cycle plots.

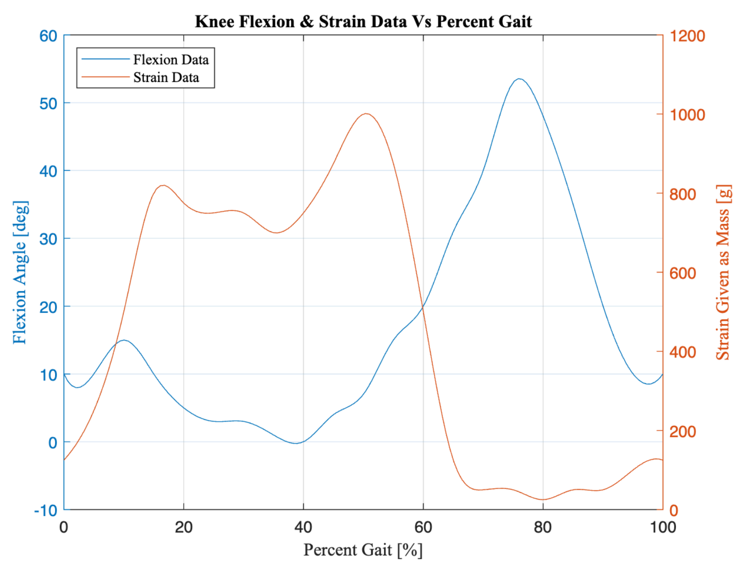

Fig 6. Knee flexion & strain data vs Percent Gait (time normalized to match phases of Gait)

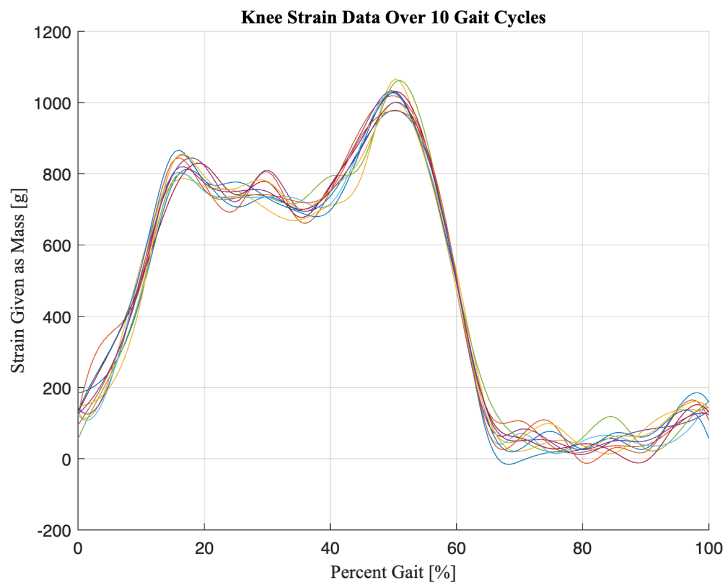

Fig 7. Knee strain data over 10 Gait cycles (time normalized to match phases of Gait)

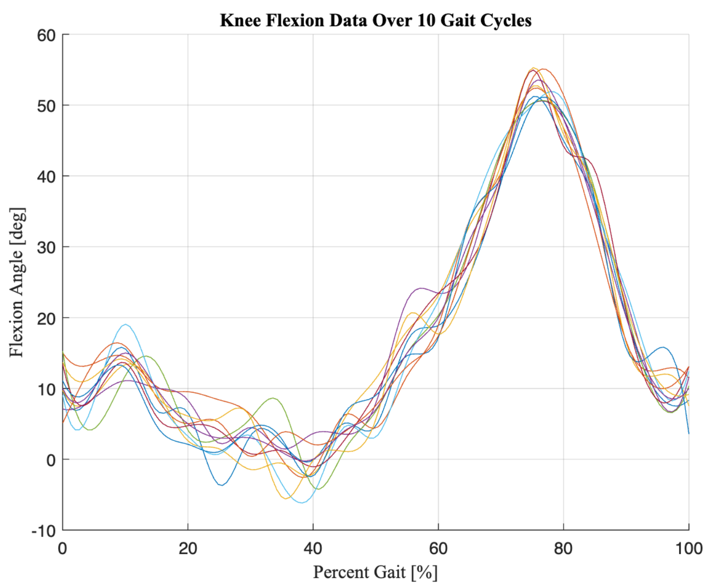

Fig 8. Knee flex data over 10 Gait cycles (time normalized to match phases of Gait)

IV. Conclusion

Due to the success of the project, I believe that the system developed in this report can be modified and improved upon to be easily implemented into the exoskeleton frame. Furthermore, the work conducted here will permeate into further projects as we can use the same data logging system to store and utilize measurements. As an endpoint of this project and report, I mocked up a PCB for the circuit described in the methodology section of this paper. There are only a few notable differences between the PCB layout and the schematic used for testing this project:

1. The highest rail on the PCB is 3.3V, which eliminates the need for all logic-level shifters used in the circuit tested
2. None of the power circuitry used in the test circuit was included into the PCB schematic

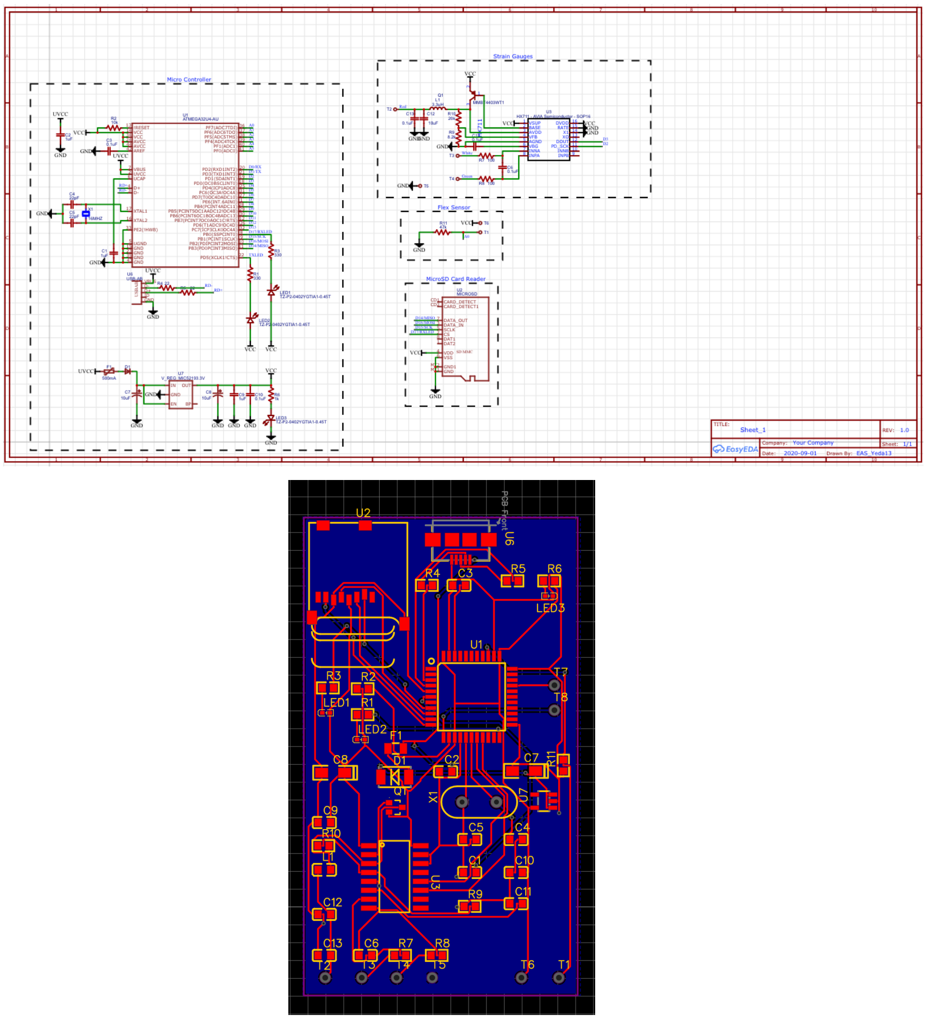

Fig 9A&B. Schematic and PCB

V. References

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