Measuring pronation and supination using accelerometers and force-sensitive resistors

UIUC Physics 398 DLP

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Introduction and Background

Project goal

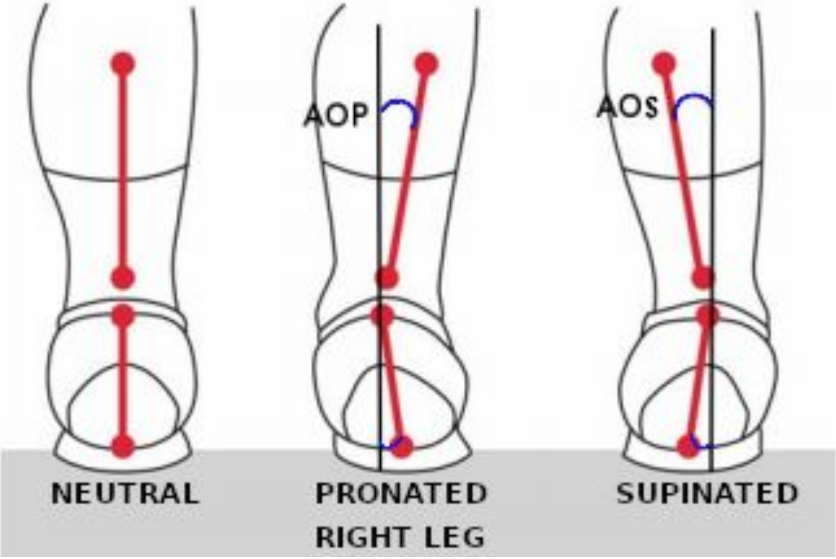
- Understanding what pronation and supination is and how to measure it can help identify the causes of injuries in runners and dancers
- Current methods cannot produce reliable and replicable numerical data
- Created an Arduino-based data logger with 3 accelerometers and 4 force-sensitive resistors
    - Collected acceleration, magnetometer, gyroscopic, and conductance data

Data acquisition device

Conducting field tests

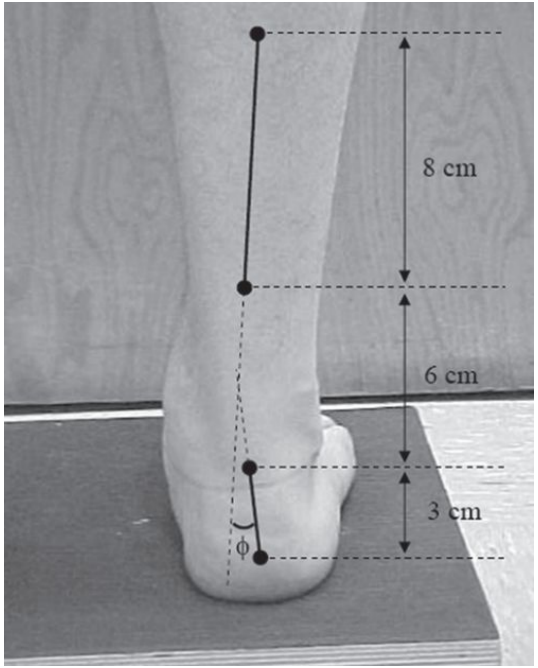
What is pronation and supination ?

- How the lower leg and heel move with respect the ankle.
- PR and SP can be qualitatively described by looking at qualities such as the foot’s arch, a person's shoe wear pattern, and surface area contact shape with a flat surface
- Measures how ankle joint moves with respect to a normal vector from the ground thought the Achilles tendon.



How pronation and supination is measured?

- The difference between both angles angles would be taken to get the angle to the right.
  - By a study from Genova and Gross.
- Pronation refers to the ankles rolling inwards
  - Angle of pronation is >10 degrees
- Supination refers to the ankles rolling outwards
  - Angle of supination is >3 degrees



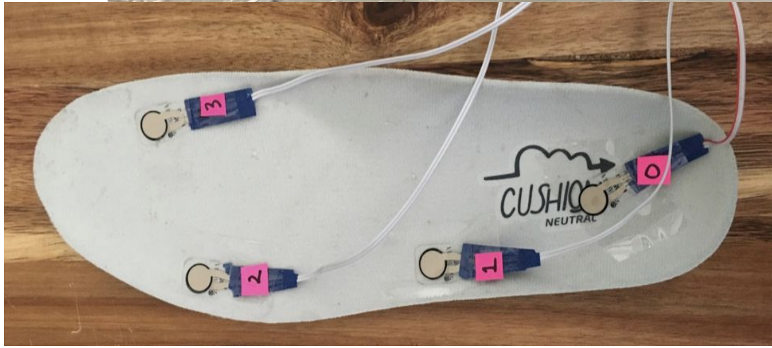
Existing Methods of Measuring Pronation Fall Short

- Pronation is typically measured on a stationary subject, using a pressure sensor
- Based on these measurements, athletes are often prescribed corrective footwear
- Donald Neumann, eminent physical therapist, has noted that there is a dearth of evidence to support this method

Given this, our goal was to develop a method that could measure pronation in a moving subject. This may allow for more helpful data to be gathered. Our hope is that other researchers can use this method to better understand pronation and supination as they relate to footwear

More on pronation and supination

- The accelerometers were placed on the leg to measure roll pitch and yaw
  - They were placed on the back of the calf above the Achilles tendon, on the back of the heel, and on top of the foot
- The force sensitive resistors were placed on the sole of the person's shoe
  - Shows which areas of the foot experienced more force during activity

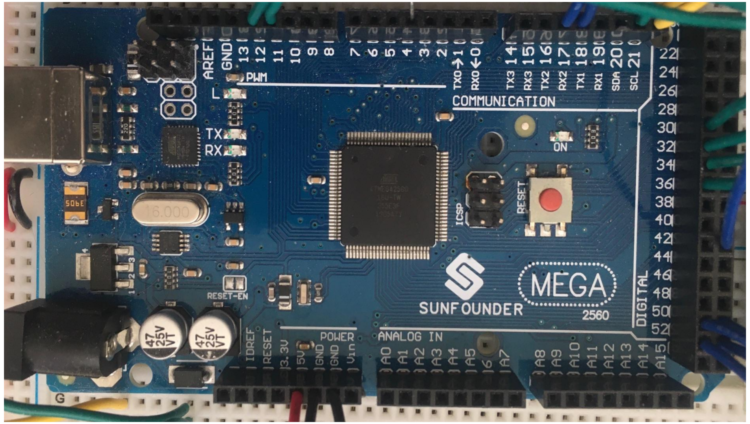


Equipment Overview

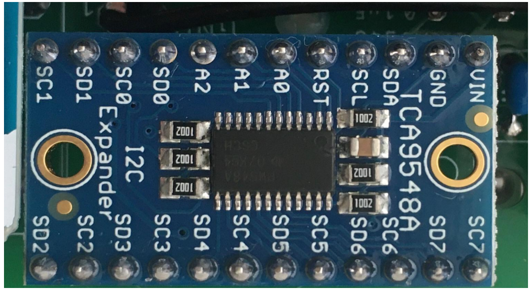
Microcontroller & I2C

- Atmel ATmega2560 microcontroller
  - Modified C++ programming
- I2C
  - Two wires for each connection, easy to use
  - Has multiple "boss" capabilities where SPI has only one
  - ideal to integrate multiple peripheral devices

- I2C uses unique identifier for each accelerometer
  - Multiplexer assigns distinct identifiers to distinguish incoming data



Arduino Mega 2560



TCA9548A Multiplexer

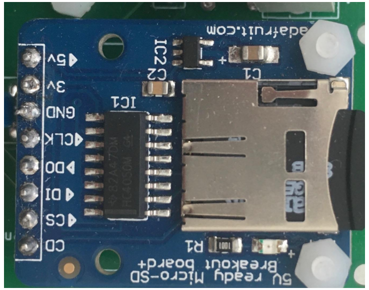
RTC, SD card, & Keypad

- RTC synchronized with GPS to create an accurate time and data for the data
- SD card stored the collected data and allowed for later offline analysis
- The keypad functioned as a start/stop key to collect individual data sets
- Used the Arduino millis function
    - Gives number of milliseconds passed since the start of program

Ultimate GPS Breakout v3

4x3 Keypad

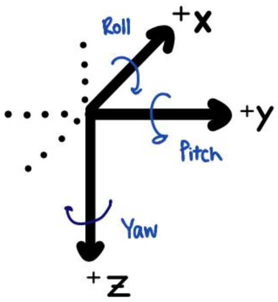
DS3231 Real-time clock

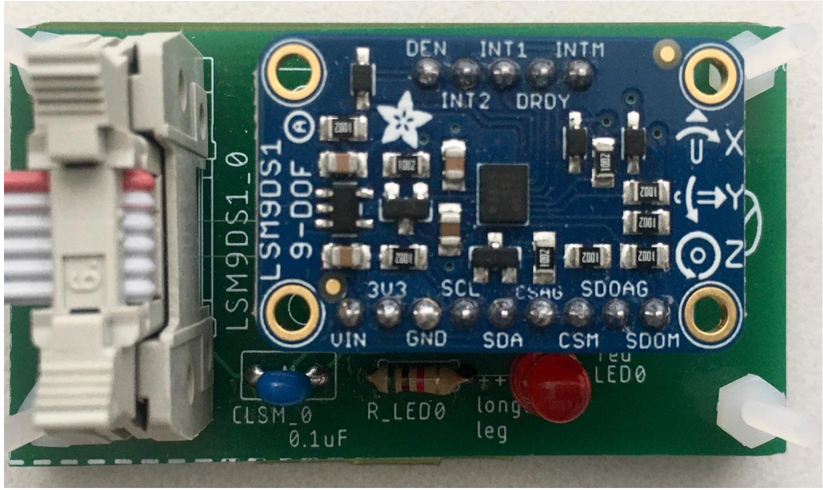


5V Micro-SD Card

LSM9DS1 Accelerometers

- Three accelerometers collected acceleration, gyroscopic, and magnetic field data
  - Did not measure desired angles, but changes in angles
  - Yaw, pitch, and roll extracted from this data

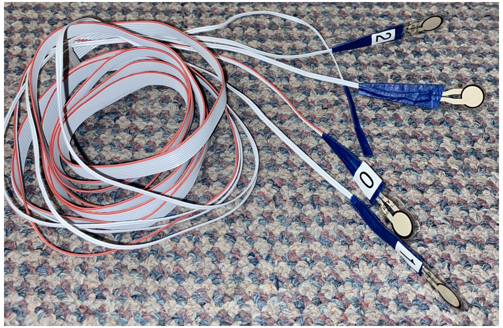




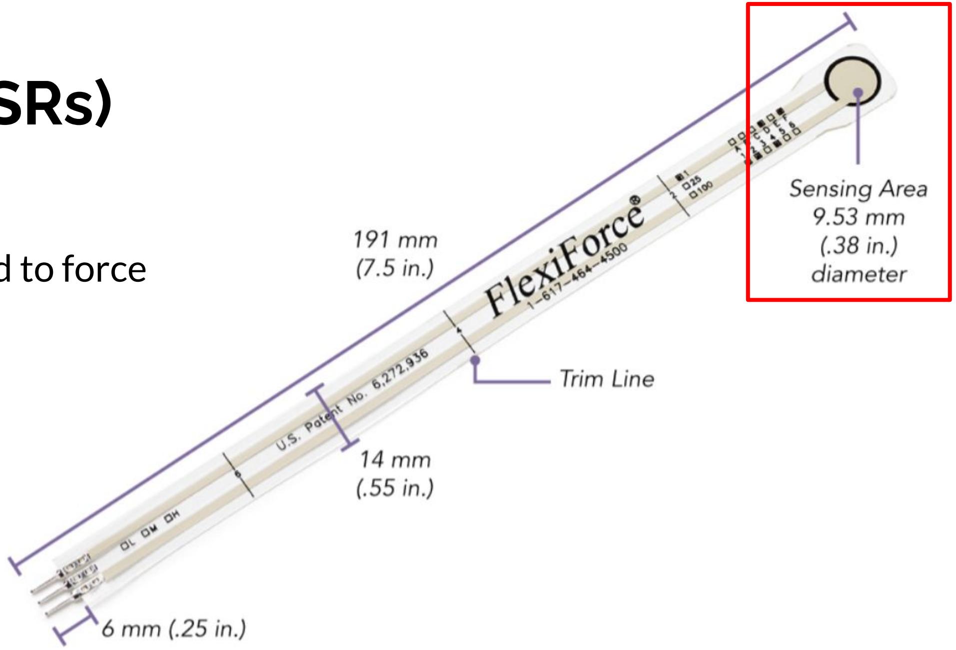
LSM9DS1 9-DOF accelerometer (x3)

Force-sensitive resistors (FSRs)

- Helps to classify accelerometer data
- Measure ADC values which can be converted to force
- Maximum force measurement of 100 lbs



Force-sensitive resistors



Tekscan FSRs

Analysis Tools

Analysis was done using Python 3.

Third-Party Libraries:

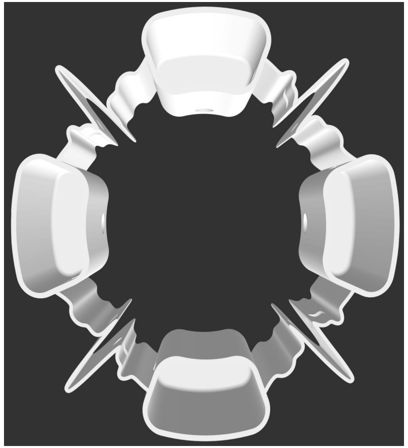
- NumPy
- Matplotlib
- Pandas
- SciPy

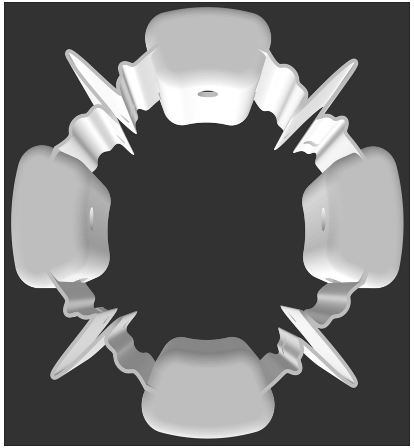
Python Software Foundation

Making & Using the Parts

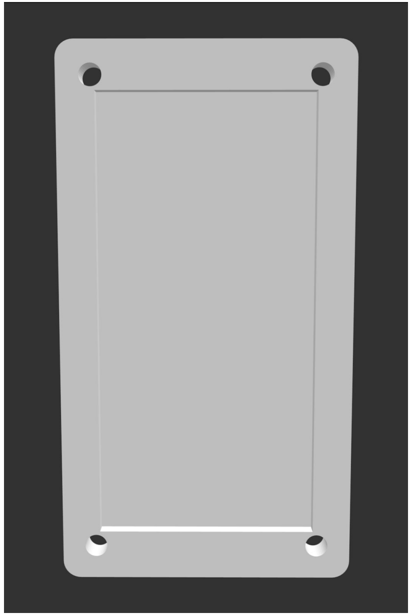
Initial Data acquisition

- Top-open health band design
  - Placed accelerometers in coplanar positions
- Printed in 85A TPU filament
  - Gave our subject freedom of movement
- Casing prevented shorting out and overheating problem





Final Hardback design



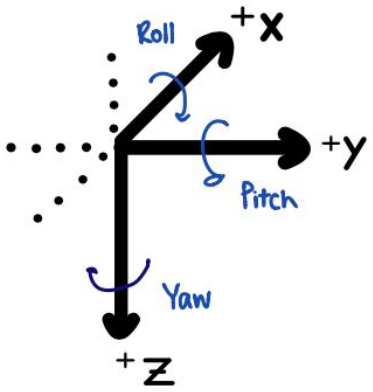
- Open design to allow accessibility to our LEDs and ribbon cables
- Each accelerometer is now separate from each other
    - We wanted different position for 3 accelerometers
- Ridges to prevent shorting problems from soldered pins coming down from below

DAC Casing

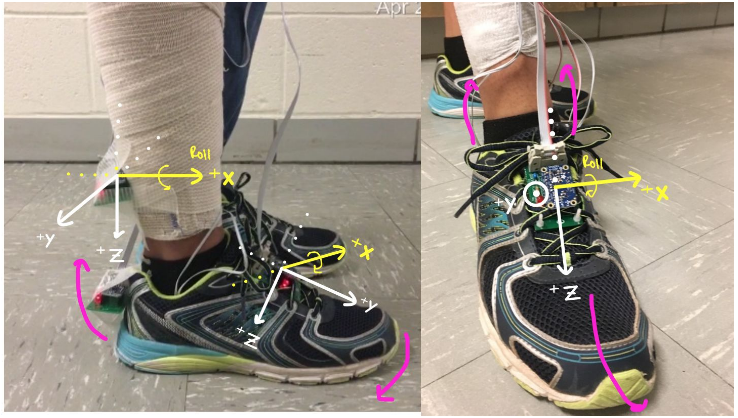
- Three lid openings above numpad, LCD and ribbon cable connections.
- One opening on the bottom of the case below the battery pack.
- Two grooves on the side of the case to insert/ pull out the lid.

Roll, Pitch, and Yaw

- Referred to as "nautical" or "airplane" angles
  - Roll is rotation around the x axis
  - Pitch is rotation around the y axis
  - Yaw is rotation around the z axis
- angular velocity (deg/s) = angular displacement (deg/s)→ angular displacement (deg)= angular velocity ((deg/s) * s)
- Implemented filter to reduce noise

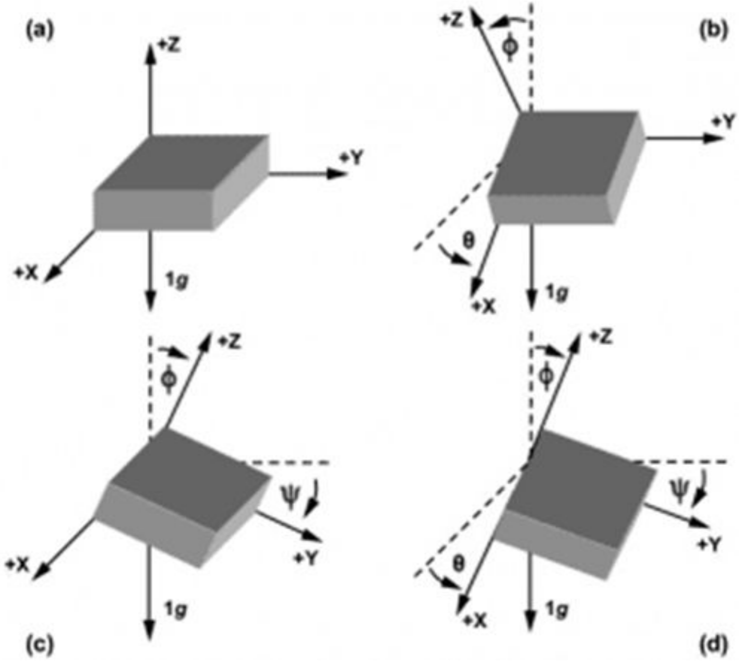


Coordinate system in experimental setup



Using Gravity as a reference

- The accelerometer can sense acceleration in x, y, z directions
  - Earth's gravitational acceleration vector can be used as a reference coordinate system.
- The angle created by the accelerometers coordinate system compared to gravity is the angle of rotation.
- Can be used well for static cases but not for fast moving cases
  - The acceleration from motion is added to the gravity creating a new vector that does not point in the direction of gravity throwing off the angle measure.



$$roll = arctan\left(\frac{ay}{az}\right) eq$$

Equation 1. Calculation for roll

$$pitch = arctan\left(\frac{-a_x}{\sqrt{a_y^2+a_z^2}}\right)$$

Equation 2. Calculation for pitch

Complementary Filter

Essentially fuses the integration and gravity methods.

- The integration value compliments those coming from the gravity method. It acts as a short term check to the extreme data that is created when in motion.
- Takes a greater percentage value from the gravity value then adds in the remaining percent from the integration value.
    - Beta is the filter coefficient which decides the percentage to take from each method.

$$angle_{complementary} = \beta * angel_{gravity} + (1 - \beta) * angle_{integrate}$$

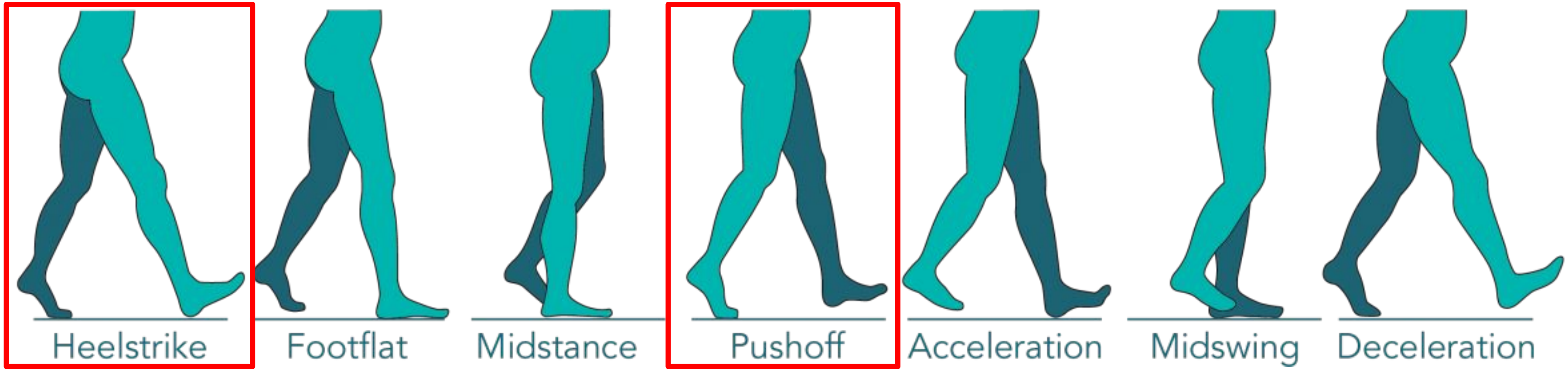
Kalman Filter

A more complex filter which uses Bayesian statistics.

- Works in two steps
  - First, it estimates the state variables and their uncertainties
  - Then, based on the actual measurement, it updates its estimates
- Tricky to set up
  - Needs to be fed several matrices
  - Not well-supported by Python

Ultimately, we decided that the effort required to implement the Kalman filter was not worth it, when the complementary filter gave us very good results by itself.

FSRs and the Human Gait Cycle



Phases of the human gait cycle (“The Gait Cycle”, 2021)

FSR Measurement

- Measures ADC values
- Can convert these ADC values to something more useful, conductance
- Given values necessary for conversion:
  - Maximum ADC value = 1023
  - ADC reference voltage = 5 V
  - Series resistance in the circuit = 10k Ohms

$$V = \frac{V_{ADC}^{ref} * ADC_{count}}{ADC_{max\ count} + 1}$$

$$R_{FSR} = \frac{\frac{V_{ADC}^{ref}}{V} - 1}{} * R_{series}$$

$$G_{FSR} = \frac{1}{R_{FSR}}$$

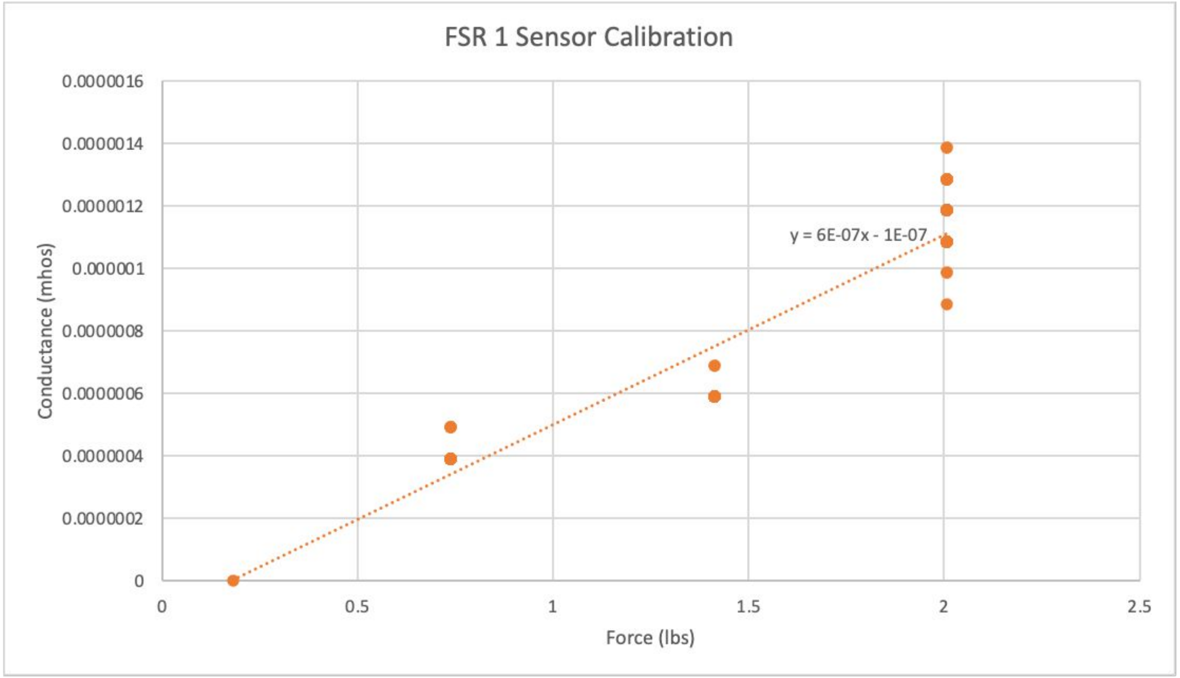
Conductance to Force

- Conductance and force relationship is linear
- Experimentally find the relationship for each sensor using known weight objects
- Concentrate the object weights onto sensing area of FSRs

Known weight objects

Object used to concentrate force

Experimental Results from Calibration

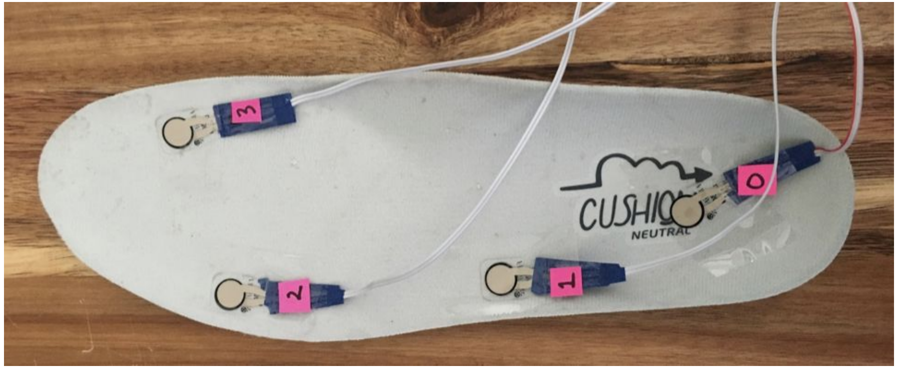


$$F = \frac{5}{3} * G + \frac{1}{6}$$

Experimental Setup

Accelerometer positions

Datalogger



Force-sensitive resistor positions

Method of data collection

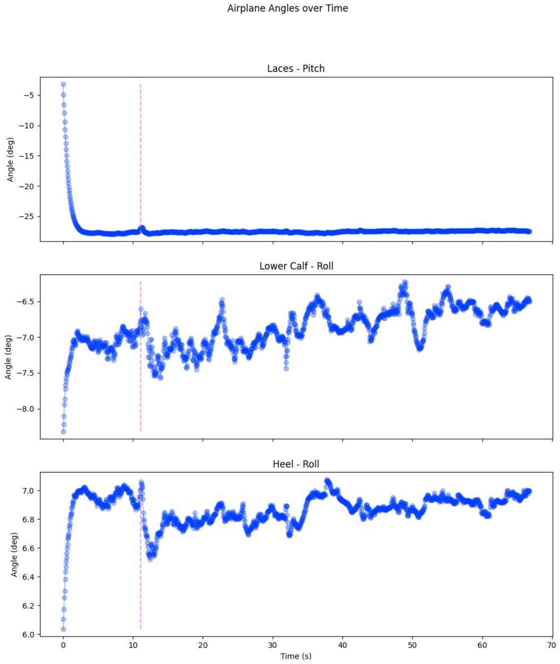
- Data acquisition program was loaded into the PCB
- LED lights then blinked for 3 seconds to indicate the setup was complete
    - To start press the “star” key (*) on the keypad
    - To stop press the “pound” key (#) on the keypad
- Subject stood still, walked slowly, walked briskly, then jogged
- Video was taken synchronously for later data analysis

Walking test

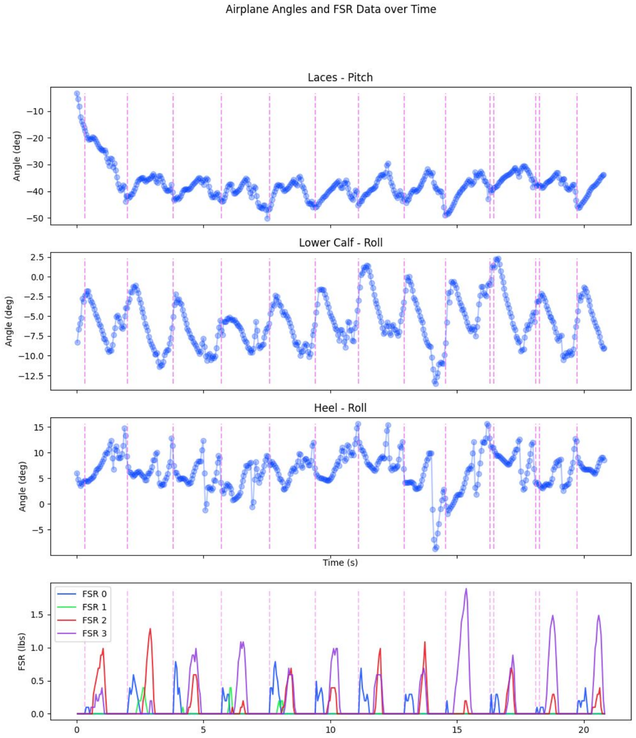
Running test

Results

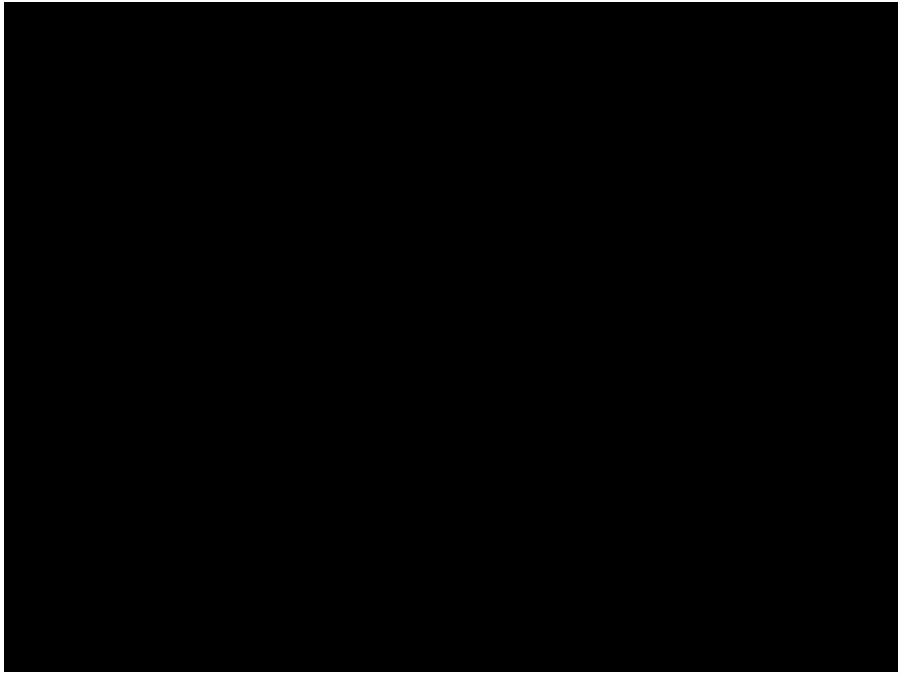
Resting Subject



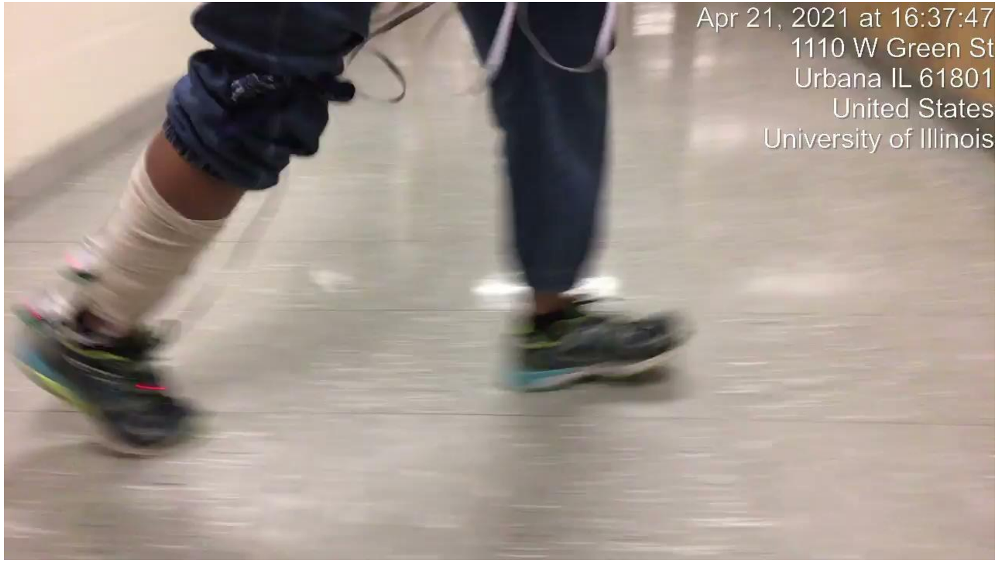
Walking Subject

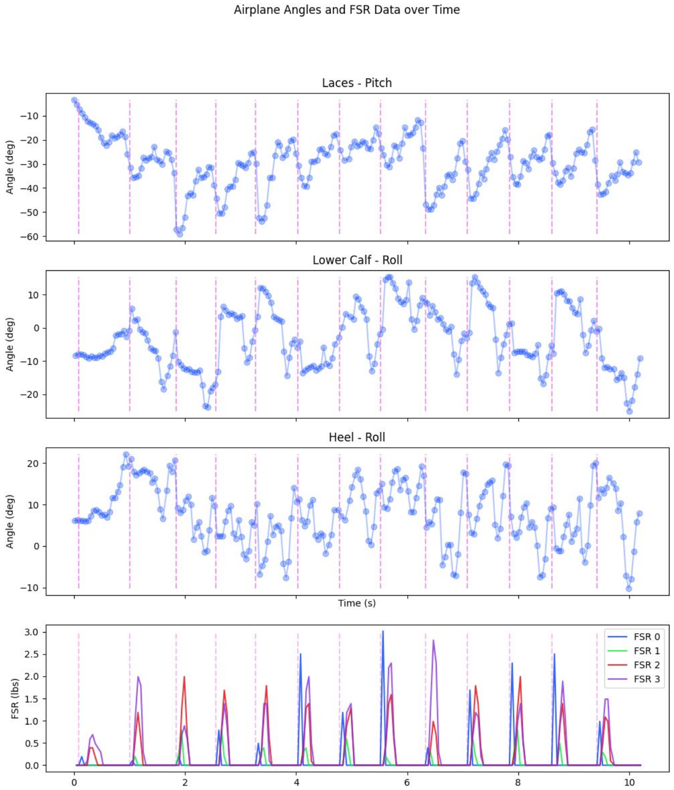


Walking Subject Force Map

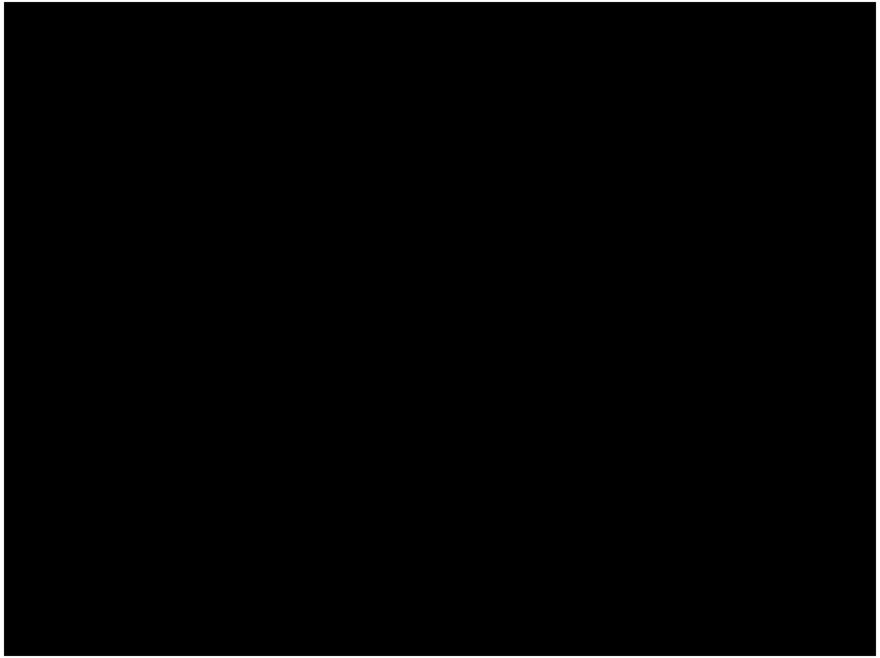


Jogging Subject



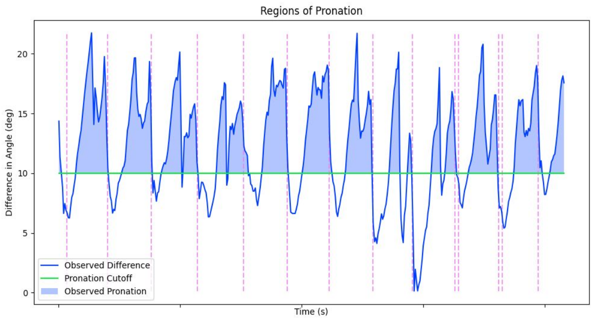


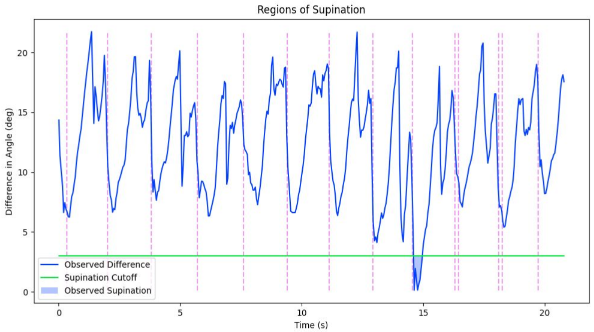
Jogging Subject Force Map



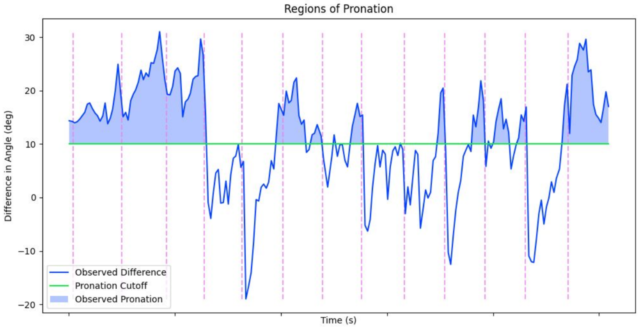
Regions

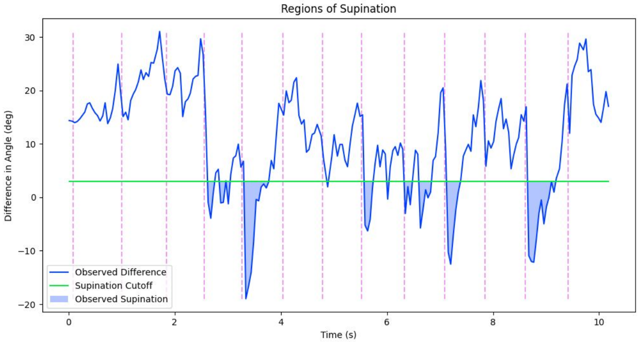
Walking





Jogging





Conclusions

Conclusion

- Using a combination of force data collected using force sensitive resistors (FSRs) and angular displacement data using accelerometers, we were able to suggest how a person's foot might pronate or supinate during dynamic motion
- Although no definite pronation or supination could be deduced, the creation of this device could prove useful in future studies with larger sample sizes

Future works

- Look at more complicated movements such as dancing
    - Forces in pointe shoes
- Take larger data sets
    - Look at longer periods of running or walking
    - Test a larger sample of people
- Invest in better force-sensitive resistors
- Implement and compare data with Kalman or other filters

Pointe shoes

Thank you

We would like to thank Professor George Gollin and Ivan Velkovsky for their guidance and the Physics Department of the University of Illinois at Urbana-Champaign for providing the materials to create our project.

Remember: Supination is like you're holding soup

References

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