SpotMe!

Synchronized **P**iezoelectric and **O**ptical **T**racking Feedback for **M**otion and **E**xercise

ECE 445 Final Report

Spring 2022

Team 3

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Abstract

SpotMe! was designed to meet the pandemic-induced lack of fitness resources such as gym spaces and trainer services. Our solution to this problem utilizes both software and hardware to detect body alignment and range of motion (ROM) respectively. The software provides the user with visual feedback for form correction while the hardware provides tactile (haptic) feedback.

We found that using a circuit that converts analog range of motion measurements into digital signals and an OpenCV model for pose estimation combined can provide the desired feedback. This constitutes a very robust and versatile solution that can be expanded to many conditions and applications (including physical therapy). We focused on providing a solution in the form of wearable technology and equipment setup for a standard living space. Outlined in this report are the problem, solution, design considerations, metrics for success and verification, as well as an analysis of cost, ethics, and safety for SpotMe!, the self-spotting gym equipment for form correction.

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1. Introduction

1.1 Problem

The primary motivation behind SpotMe! is the prolonged and prominent effects of COVID-19 on increasing sedentary lifestyles [1] for most citizens of the world. Quarantine conditions around the globe removed a lot of daily motion from peoples' lives, and a transition to remote work for more than two years has drastically influenced fitness levels for all those affected. For those wanting to reintroduce motion and exercise into their daily routines, there is still an ongoing unavailability of resources and gym spaces, so working out from home is the only option. Without the aid of personal trainers or friendly gym-goers, people new to fitness can seriously injure themselves. Aside from not receiving the benefits of certain motions, there is an increased likelihood of injury when people do body-weight movements incorrectly. The two metrics for this are defined as ROM and body alignment. Furthermore, if we take a look at the body-weight lunge, incorrect ROM does not activate the larger leg muscles, and not aligning the knee behind the toes increases the stress placed on the injury-prone knee joints.

1.2 Solution

Our solution for this problem has two main subsystems: a set of piezoelectric-based sleeves for the knees and a computer-vision-based software. The combination of these two measurement systems address the primary functions of this device: to measure the ROM and the body alignment. Thus, our solution is a wearable device that utilizes a three-camera system to capture different angles of motion. This has the capability to provide corrective feedback while in use. This solution is specified for the body-weight lunge, one of the most dynamic and functional calisthenic movements.

We note that the two main subsystems are not required to communicate with one another to achieve the metrics of success that we define below. In fact, this independence feature is what allows both subsystems to function well together and in real-time.

1.3 Visual Aid

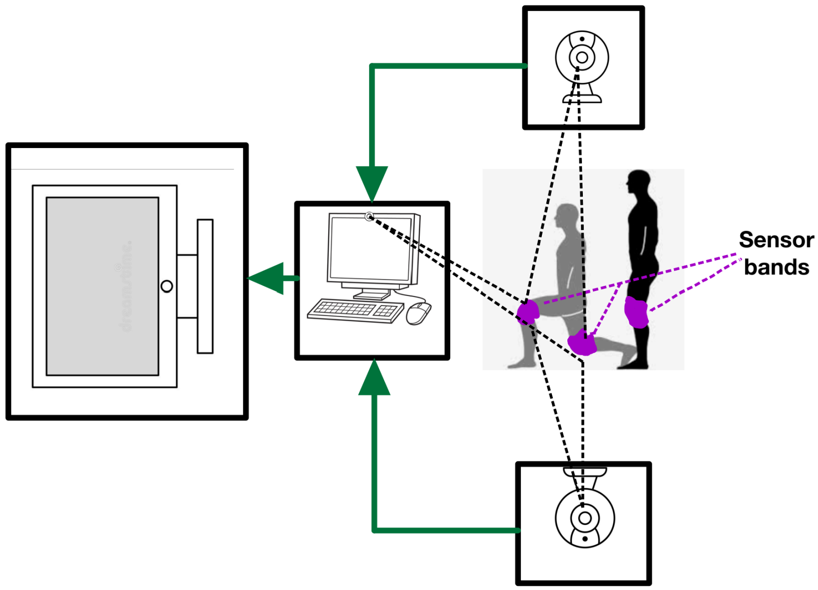

Figure 1. *Visual aid for proposed SpotMe! Solution*

1.4 High Level Requirements

- The software must be able to identify three key points of alignment (feet, knees, hips) and relay full body position back to the user through the computer display.
- The hardware sleeves must be able to measure 85-90 degree ROM and accurately provide feedback to the user once the correct ROM has been achieved.
- The device must run on battery-power limitations (6 V) and the knee sleeve must compactly house the PCB, motor, and sensor.

1.5 Subsystem Overview

In total, there are five subsystems in our design, two of which are summarized as user input and output. The remaining three will be the wearable unit subsystem, the computer vision subsystem, and the power subsystem. The connections and communication between subsystems is summarized in Figure 2:

1.5.1 Block Diagram

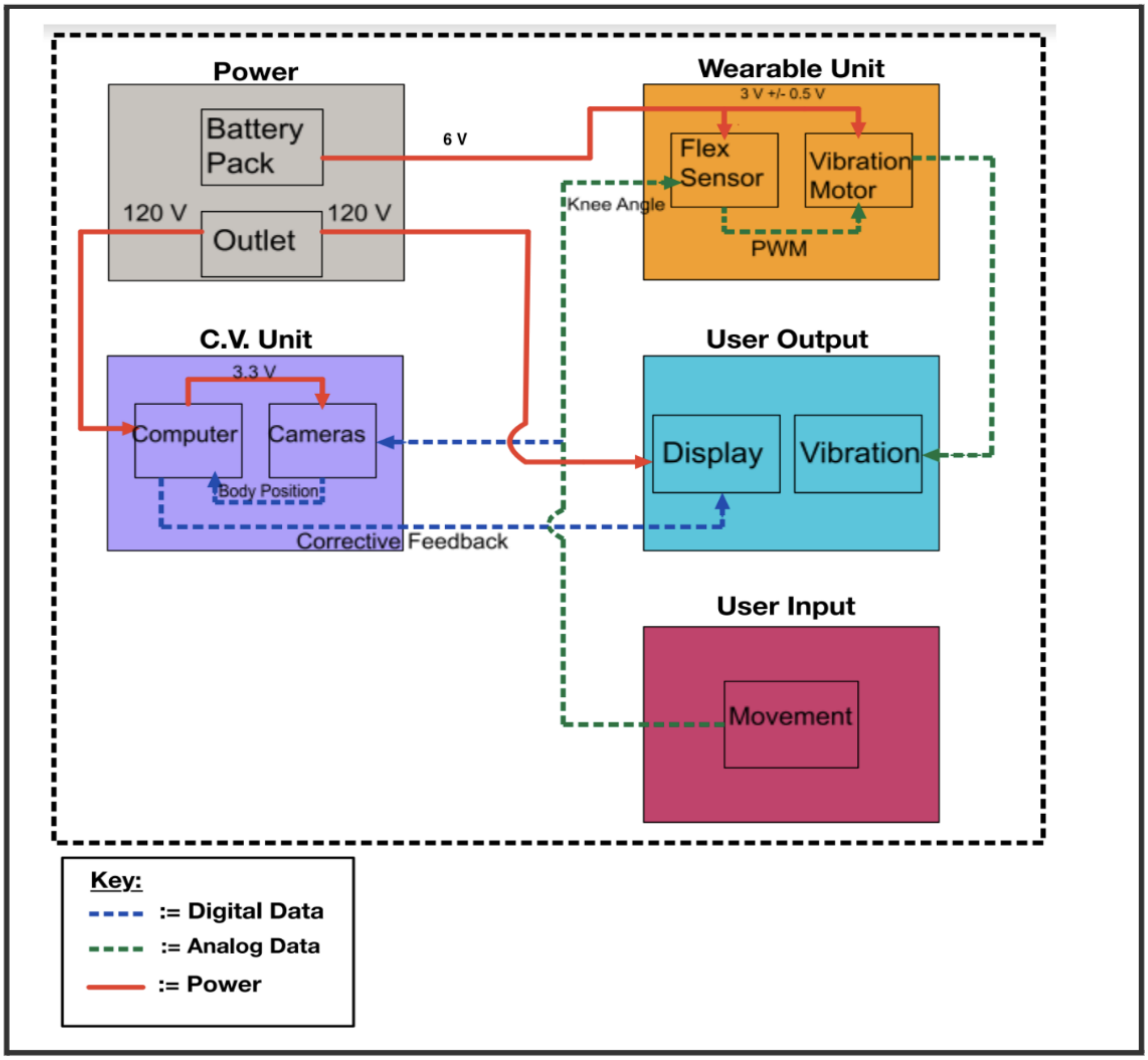

Figure 2. *Block Diagram for Proposed SpotMe! Solution*

Note the distinction between analog and digital signals between subsystems. All power connections are labeled with red solid lines, dashed lines indicate data used in computations (even by the hardware). User input and output are separate subsystems for clarity.

2. Design

2.1 General Considerations

In order to effectively solve this problem, the variation in anatomy among humans was addressed by making both the hardware and software components as variable as possible. For the wearable device, the knee sleeve and ROM detection was made to be adjustable to the individual. For the computer vision subsystem, the key point identification and pose estimation algorithm utilized several features of the body to properly execute its function. The wearable sleeve also had to operate at low-voltage and current specifications, which introduced challenges during the design processes, met with different approaches to yield the final product.

Also, the wearable technology is detecting the ROM as an analog signal that is user-specific, and that subsystem is capable of removing the dependence on the user by utilizing CMOS technology and a tunable voltage divider to meet one threshold condition.

2.2 Physical Design

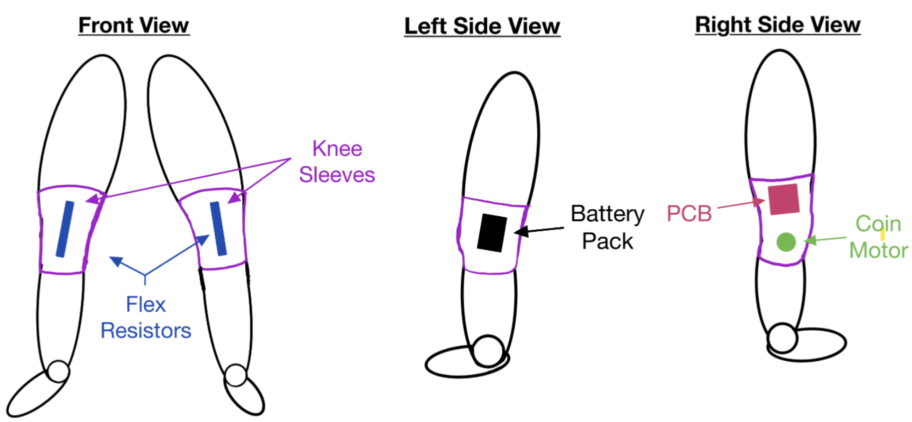

Figure 3. *Diagram for the Physical Design of Knee Sleeves*

The knee sleeve is the exterior component that houses all of the hardware. The hardware component, namely the PCB, utilizes flex sensors, coin motors, and a battery pack to carry out its function. As seen from the diagram above, the flex sensor is placed along the length of the knee cap to measure flexion of the knee and measures ROM for the movement. The PCB and the battery pack are put to either side so as to not obstruct user movement. The coin motor is put under the PCB and close to the skin to provide the haptic vibration feedback at movement completion. Not pictured, but an extended part of the PCB is the tuning potentiometer that allows the hardware to be independent of the user's anatomy.

2.3 Circuit Design

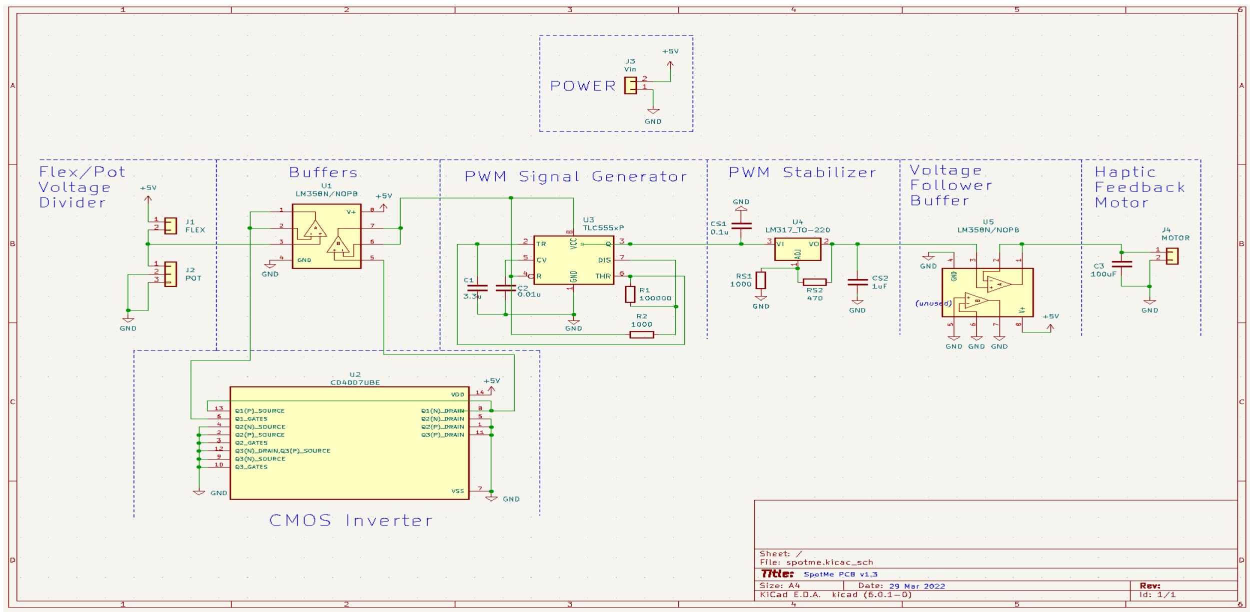

Figure 4. *Circuit Schematic for SpotMe!*

An enlarged version of the schematic can be found in Appendix A. The schematic combines the power and wearable subsystems to display how the analog ROM measurement from the tunable voltage divider is converted to a digital signal via the CMOS inverter, which is turned into a pulse by the 555 Timer, stabilized by the LM317, decoupled by a capacitor to further smooth the signal, and relayed as a 2 Hz vibration feedback by the coin motor. The voltage divider will decrease its output voltage as the flex sensor bends and its resistance increases. How much so depends on the resistance of the potentiometer, which is adjusted to each person's ROM to cross the threshold of the inverter.

To achieve a 50% duty cycle and 2 Hz vibration, the following equations and component values were used [2]:

$$Duty\ Cycle = \frac{R_1}{R_2 + 2R_1} \quad where\ R_1 = 100\ k\Omega\ and\ R_2 = 1\ k\Omega \Rightarrow Duty\ Cycle = 50\%$$

$$Frequency = \frac{1.44}{(R_2 + 2R_1)C}\ where\ R_1\ and\ R_2\ same,\ C = 3.3\ uF \Rightarrow Frequency \approx 2\ Hz$$

The few design changes that were made from our initial implementation do not deviate from the high-level skeleton described. The current draw from the circuit was too high to be sustained for longer than 30 seconds by two 3.3 V coin cell batteries, and were thus swapped with 4 AA batteries that could sustain the current draw based on their mAh specifications. LM358N Op-Amps were used as voltage-follower buffers after every stage in the circuit to solve the large voltage drop-offs that were occurring as a result of varying device impedances.

2.3.1 Part Specifications and Considerations

There are a lot of design changes that were made during the design process. One of the things that changed was swapping the Schmitt Trigger inverter with a CMOS inverter [3].

$$V_{T,\,CMOS} = 1.4\,V\ on\ rising\ and\ falling\ edge\ of\ input$$

The reason for this was because of the asymmetrical threshold voltages between the rising and falling edges of the input. This would result in the vibration motor triggering at different points during the lunge movement, which is not what our device is designed to do. Voltage drop-offs between different blocks of the circuit forced us to change our design and add inverting op-amps to maintain the same voltage between the higher level blocks, otherwise there would not be enough voltage to power the motor. Adding these voltage buffers allowed us to solve the problem. The voltage divider between the flex sensor and potentiometer made us consider each one’s range of values in order for our circuit to function correctly. Values for different resistances are tabulated and adjusted to receive the 3:1 ratio between the potentiometer and flex sensor. Another thing that was adjusted was the power source. Switching to four AA batteries from the original coin cells provided our circuit with much more current to allow our device to run for much longer. Our original knee sleeve was slightly too loose, so a knee sleeve that was much tighter, yet still retained elasticity, was purchased to snugly house the battery pack, PCB, motor, and flex sensor.

Pictured in Appendix A is the characterization of the flex sensor and potentiometer. There is roughly a cap of about 30 kΩ on the flex sensor at 90 degrees of flexion. This was the basis for choosing the 100 kΩ potentiometer for increased sensitivity. If the resistance of the potentiometer is too low, then the feedback would be constant and the threshold would not be met.

2.3.2 Fabricated Circuit

[Images of the PCB layout and fabricated device are in Appendix A.]

2.4 Computer Vision

Correct form for an exercise consists of two elements: complete ROM and proper body alignment. The computer vision in SpotMe! tackles the latter by tracking the user's body positions, specifically the joint positions, as shown in Figure 5. With the joints tracked, detecting incorrect form is done by simply calculating the distance, along the x or y axis, between two joints and then applying conditional logic.

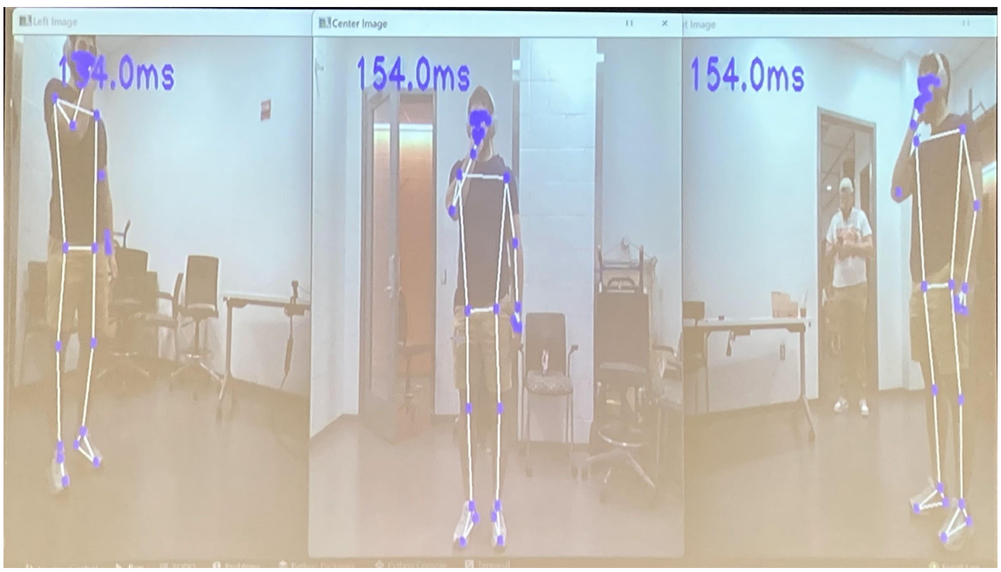

Figure 5. *Pose Estimation Example*

We utilized the MediaPipe Pose model to do the human pose estimation and OpenCV to process the camera feeds. MediaPipe Pose calculates the human pose in two high-level steps[4]. First, the model detects the human in the frame and calculates a bounding box. Note, the bounding box is the smallest rectangle that completely encloses the detected human. The smaller image within the bounding box is then used as the input for the pose estimator[4].

The setup for the computer vision involves three cameras, a display, and a computer. Three cameras are used so that the corrective feedback for the lunge is accurate and robust. The three cameras get the front, left, right side angles of the user to cover all angles of the lunge movement that will be analyzed for improper form. All three camera feeds are inputs into the computer, which processes the human pose estimation and corrective feedback program. Finally, the output of the program is displayed with the user's pose overlay and visual corrective feedback (Figure 6).

Figure 6. *Example Output of Computer Vision Program with Corrective Feedback*

2.4.1 Computer Vision Design Considerations

The main considerations for the computer vision implementation involved having cameras with little to no local processing and a human pose estimation model that could process fast enough to have a low latency project. In our first implementation we tried to use a Microsoft Kinect camera as the video feed input to our program. However, the Kinect did not interface well with OpenCV and could not act as a stand alone video feed. The Kinect has its own internal image processing so when using it with OpenCV the video took longer to read and had poor color accuracy. This caused us to switch to normal webcams which did not have internal processing and easily interfaced with OpenCV.

MediaPipe Pose was chosen as our model of choice because it is able to do the human pose estimation in the constraints of a low latency environment. Since we want SpotMe! to give real time feedback, low latency image processing was a necessity.

2.4.2 Computer Vision Implementation

<u>Corrective Feedback Calculations</u>:

```
Let left_knee := (left_knee_x, left_knee_y)
Let right_knee := (right_knee_x, right_knee_y)
Let left_toe := (left_toe_x, left_toe_y)
Let right_toe := (right_toe_x, right_toe_y)
Let left_hip := (left_hip_x, left_hip_y)
Let right_hip := (right_hip_x, right_hip_y)
```

1. **Hip Alignment:**

Left Hip

```
dif = int(left_hip_y-right_hip_y)
if dif > 10:
    // left hip above right hip
    Draw up arrow

elif dif < -10:
    // left hip below right hip
    Draw down arrow
```

Right Hip

```
dif = int(right_hip_y-left_hip_y)
if dif > 10:
    // right hip above left hip
    Draw up arrow

elif dif < -10:
    // right hip below left hip
    Draw down arrow
```

2. **Knee Over Toe:**

Left Knee

```
if (left_knee_x - left_toe_x) <= -7:
    //left knee in front of left toe
    Draw left arrow
```

Right Knee

```
if (right_knee_x - right_toe_x) <= 7:
//right knee in front of right toe
```

```
Draw right arrow
```

3. Knee Touching Floor

Left Knee

```
if (left_knee_y - left_toe_y) > 30:
    //left knee on floor
    Draw up arrow
```

Right Knee

```
if (right_knee_y - right_toe_y) > 30:
    //right knee on floor
    Draw up arrow
```

3. Cost & Schedule

Labor Costs

Engineer	**Arjun**	**Pablo**	**Jason**
Rate	$33/Hour	$33/Hour	$33/hour
Hours per Week	10	10	10
Weeks to Completion	9	9	9
Total Labor Cost per Member	$2970.00	$2970.00	$2970.00
Total Labor Cost	**$8,910.00**		

We used an average hourly wage for a part-time electrical and computer engineering intern from our personal experiences to calculate what the labor cost of this project would be. From the moment our design was reviewed and approved by administration, we had nine weeks to complete our project. Assuming the part-time co-op students would work ten hours per week, the total labor cost would be $8,910.00.

The total parts cost is tabulated in Appendix B, and due to our particular selection of materials, the cost was reduced and totaled $133.98. Now, the grand total is $9,043.98.

Total Costs

Labor Costs	**Parts Costs**	**Grand Total**
$8,910.00	**$133.98**	**$9,043.98**

4. Design Verification

The requirement and verification tables for each subsystem are located in Appendix C for clarity. Here, we offer a brief discussion of the requirements, as there is only one requirement that was not met in its entirety, and that lies within the computer vision subsystem.

4.1 Power Subsystem

We set out to make a power subsystem that would supply the currents necessary for the circuit to function. As mentioned in the design considerations, the quad AA battery supply met the criteria in our requirement-verification table. We verified the terminal voltage of the battery pack at 6.4 V which is above our 90% of nominal voltage minimum to consider the battery charged. We verified the reasonable current draw with the DC power supply, and used a multimeter at the supply pins of each IC (except the timer) to verify their direct connection to the power source.

4.2 Wearable Subsystem

We set out to design our wearable subsystem to meet the requirements of providing tactile feedback to the user once the 85-90 degree ROM is achieved. This is verified when the user calibrates the device while initially bending the knee to the desired angle and verifying that vibration occurs at the specified angle.

4.3 Computer Vision Subsystem

For SpotMe! to be complete and robust, it is vital for the computer vision subsystem to provide clear and corrective feedback in real-time. Before feedback can be provided, the user's whole body must fit into all three camera frames simultaneously throughout the entire lunge movement. To verify this the user stands in front of the cameras and performs a lunge movement while watching the display. If at any point their whole body is not in a camera's frame then the camera should be adjusted. Repeat this process until the user's body is in frame for all cameras during the complete lunge movement.

There are also eight key-points: hips, knees, ankles, and toes, that need to be detected in all camera frames throughout the lunge movement. To verify, the user stands in front of the cameras with the pose-estimation program running and does a lunge movement. If the keypoint overlay is displayed the entire time then this requirement is met.

The main visual requirement for the computer vision is the performance of the provided corrective feedback. The following constitutes incorrect form:

- Front knee is past toes
- Back Knee is touching the floor
- Hips are asymmetric

To verify the corrective feedback is accurate the user purposefully performs the lunge movement incorrectly and visually verifies that the screen displays the correct feedback. For example, the user purposefully does a lunge with the left knee touching the floor. The correct visual feedback should be an arrow starting at the left knee and pointing upwards.

Since the computer vision subsystem needs to provide real-time feedback the software needs to maintain low latency. To verify this the difference in time from reading the current video frame and outputting the modified frame to the display is calculated. For clarity consider the following:

- Let ***x*** be the time at which the current video feed frame is read by the program
- Let ***y*** be the time at which the current frame has been processed by the software and displayed
- Then ***Latency = y - x***

4.4 User I/O

The only verification for these two subsystems needed was visual display of the feedback after having the user attempt a body-weight lunge to completion. This was verified multiple times during the demonstration.

4.5 High Level Requirement Verification

The computer vision algorithm was able to identify more than just the key points that we needed, as it was based on having the entire human in the frame. That was verified by the display during the demonstration. The 85-90 degree ROM was verified by the tuning potentiometer’s flexibility in setting the unique threshold for Pablo, Arjun, Jason, and even the TA Shivang. The power supply was still effectively at six volts.

5. Conclusion

5.1 Accomplishments

The project that we set out to complete was brought to fruition. We developed a product that would meet the needs for measurements of ROM and body alignment for form correction. This product met the high-level requirements of identifying key points of alignment, being tuned to the correct ROM, and running under certain power limitations. The specific subsystem requirements were verified. The latency of the computer vision subsystem is affected by the multi-camera feed, but otherwise the latency is still imperceivable for the rate of motion. The challenges that we met during the testing and debugging phases were overcome with application of theory from some other courses within the ECE core curriculum. Both the hardware and software components exemplified great robustness to the body shape of many users and in many asymmetric room configurations.

5.2 Ethics & Safety

Our project does not breach any ethical guidelines on the basis of discrimination because it is meeting a need that serves a general community of those affected by the pandemic, independent of race, ethnicity, gender, and sexual orientation. This device does have a target audience of people without excessive limb loss in their lower extremities as it is designed to be wearable technology that measures the flexion of the knee. However, that is a necessary feature for the hardware component solution and therefore is not discriminatory. Our device, therefore, complies with section 7.8.II-7 of the IEEE Code of Ethics.

The use of OpenCV software does not record or harbor any personal data or imagery other than what is necessary for its intended purpose of real-time feedback. User identity is not a factor in our device solution, therefore protecting the privacy of the user, complying with section 7.8.I-1 of IEEE’s guidelines [5].

We avoid presenting our solution in esoteric terms and make our device specifications easily understandable for the general public’s use, which improves the understanding of individuals and society as described by guideline 7.8.I-2.

Other guidelines are not applicable to the project but to each of our team members as individuals, and we aim to abide by and hold each other accountable to these guidelines as specified by 7.8.III-10.

Our solution delves into the realm of wearable technology, which has its own guidelines and regulations. The wearable component does not track any personal information, nor does it provoke a false sense of safety or unnecessary anxiety with the data that is taken and the feedback that is given. The wearable devices are low-voltage and will not pose a threat to the user, and they will be added to commercially available knee sleeves. We integrate the device on the outside (forward-facing) of the knee, but because the flex sensor supports bi-directional flexion if the user sports the equipment incorrectly, it won’t necessarily interfere with the results or harm them in any way, so long as they align the device with one of the two directions of flexion.

All engineers should also have a commitment to sustainability. Our design will optimize our part list to maximize the product life cycle. We will test a few power sources and see what works best for the device, and try to make it as sustainable as possible. Due to the availability of rechargeable AA batteries, the product life cycle can be extended if the user opts to use those as opposed to single-charge batteries.

5.3 Future Works

Our original intent with this idea was to apply it to all body weight exercises not limited to the lunge. This includes push-ups, squats, dips, and more. As our device utilizes flex sensors that measure concentric and eccentric movements at the joints, additional sleeves can be fabricated for the elbows. Inertial measurement units can be added to the elastic sleeves to track the speed of movement and to better track ROM if we were to fabricate this device again. Another addition to the current design is to add the ability to track user exercise history, as it is crucial to check your progress and continuously show improvement. However, we were working under budget and time constraints, so we followed through with a design that we knew would work. Expanding this design can allow for usage in physical therapy where the goal is to help patients regain their ability to improve ROM and flexibility.

References

[1] Kaur, Harleen, et al. “Physical Fitness and Exercise during the Covid-19 Pandemic: A Qualitative Enquiry.” *Frontiers in Psychology*, Frontiers Media S.A., 29 Oct. 2020, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7673425/.

[2] “LM555 Timer.” *Data Sheet, Product Information and Support | TI.com*, https://www.ti.com/lit/ds/symlink/lm555.pdf

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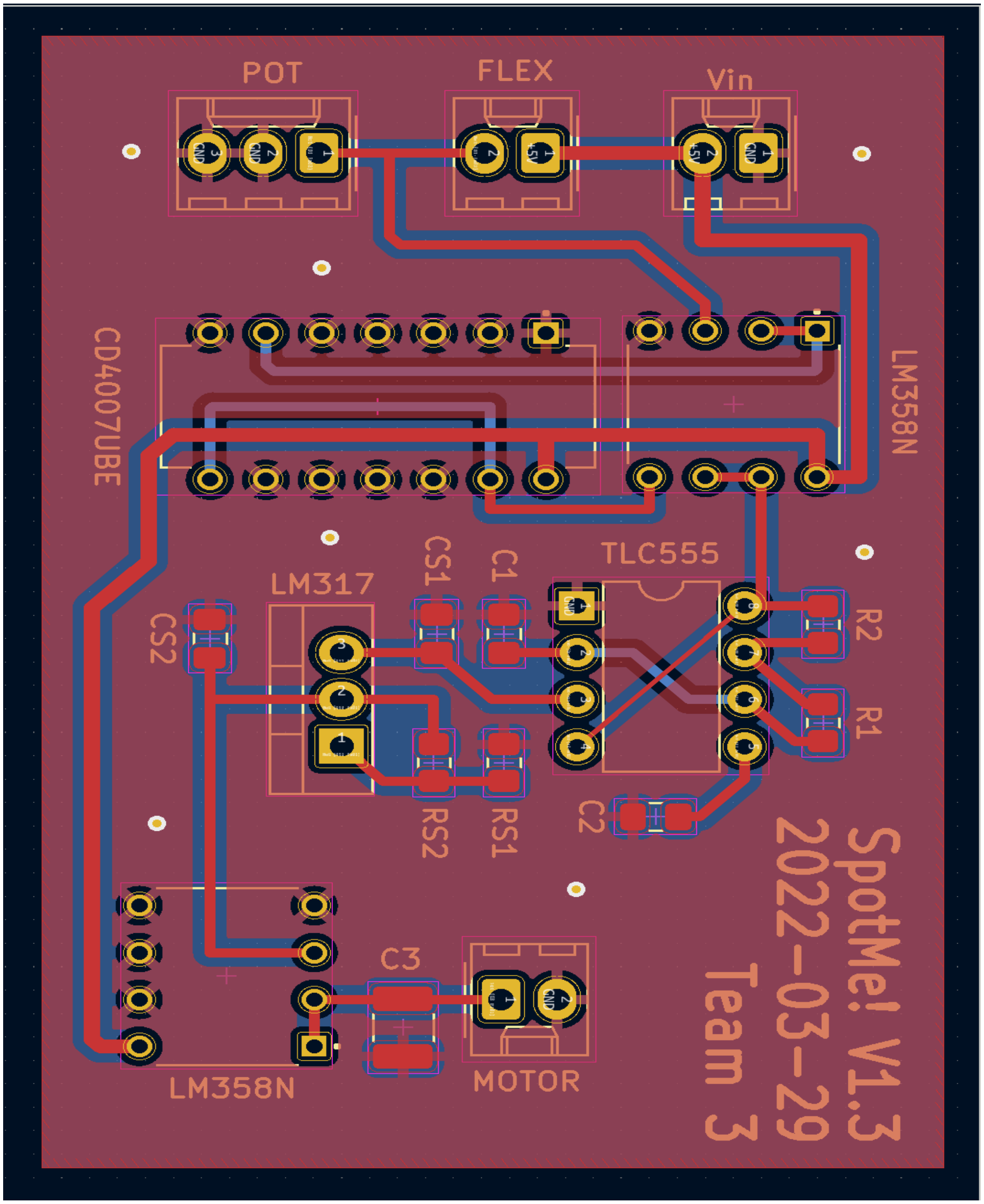
[4] Google LLC. (2020). Pose. mediapipe. Retrieved May 4, 2022, from https://google.github.io/mediapipe/solutions/pose.html

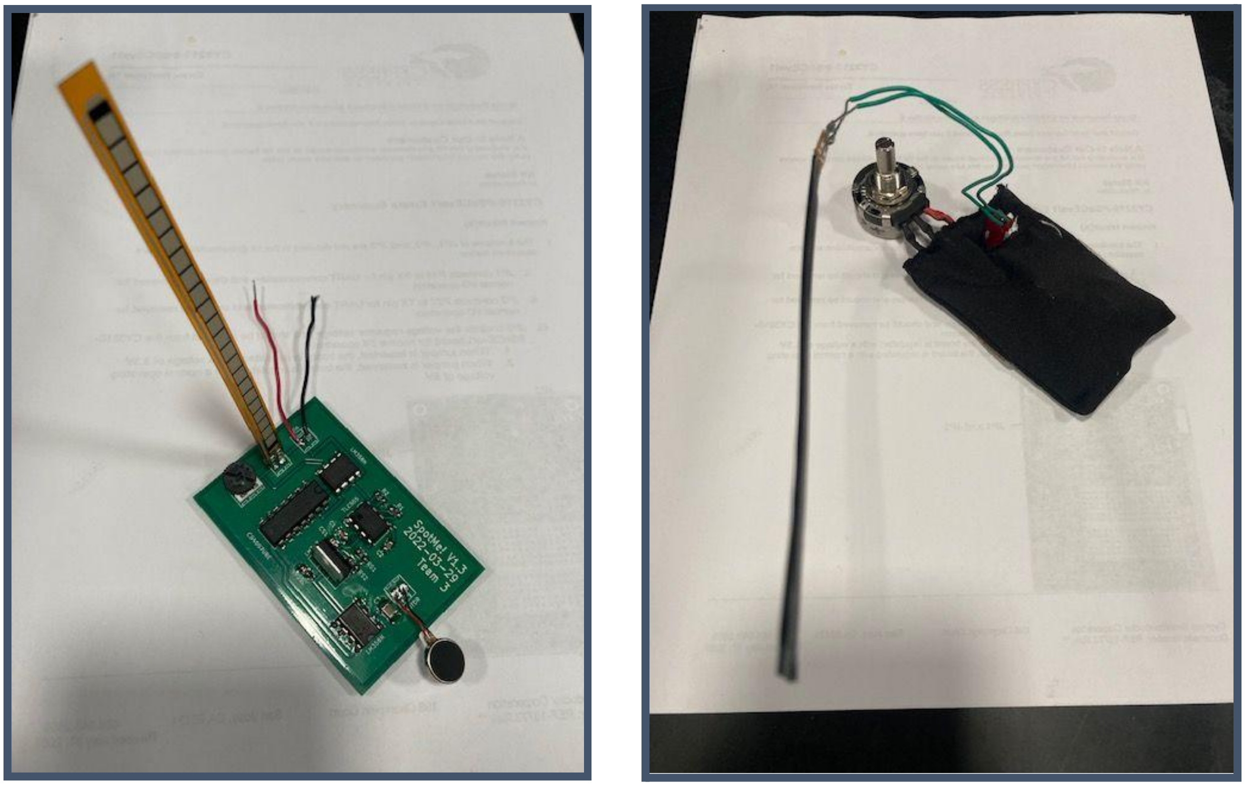
[5] “IEEE Code of Ethics.” *IEEE*, https://www.ieee.org/about/corporate/governance/p7-8.html.

[6] Flex Sensor 4.5” *Datasheet* https://cdn.sparkfun.com/datasheets/Sensors/ForceFlex/FLEXSENSORREVA1.pdf

Appendix A: Visuals

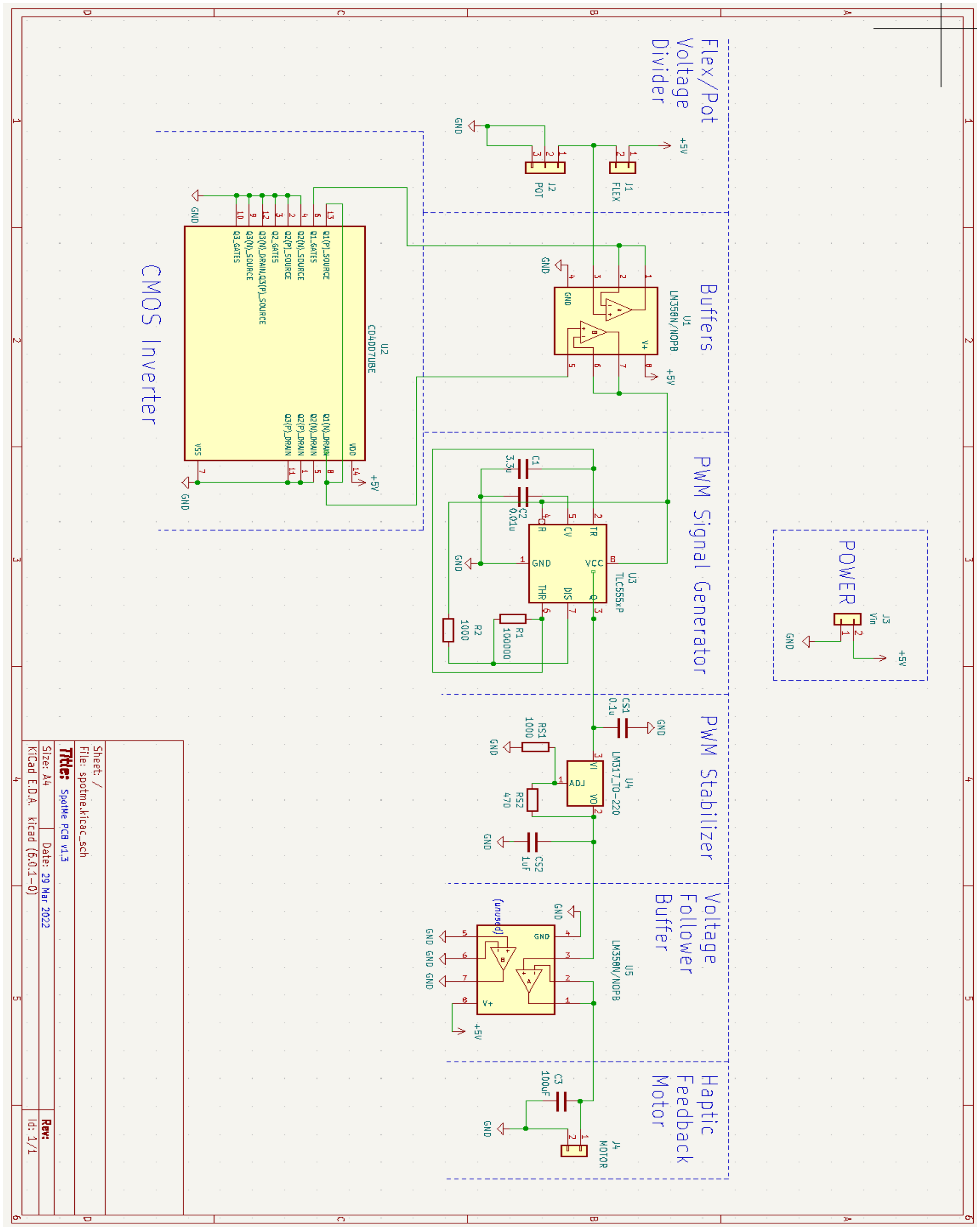


PCB Layout

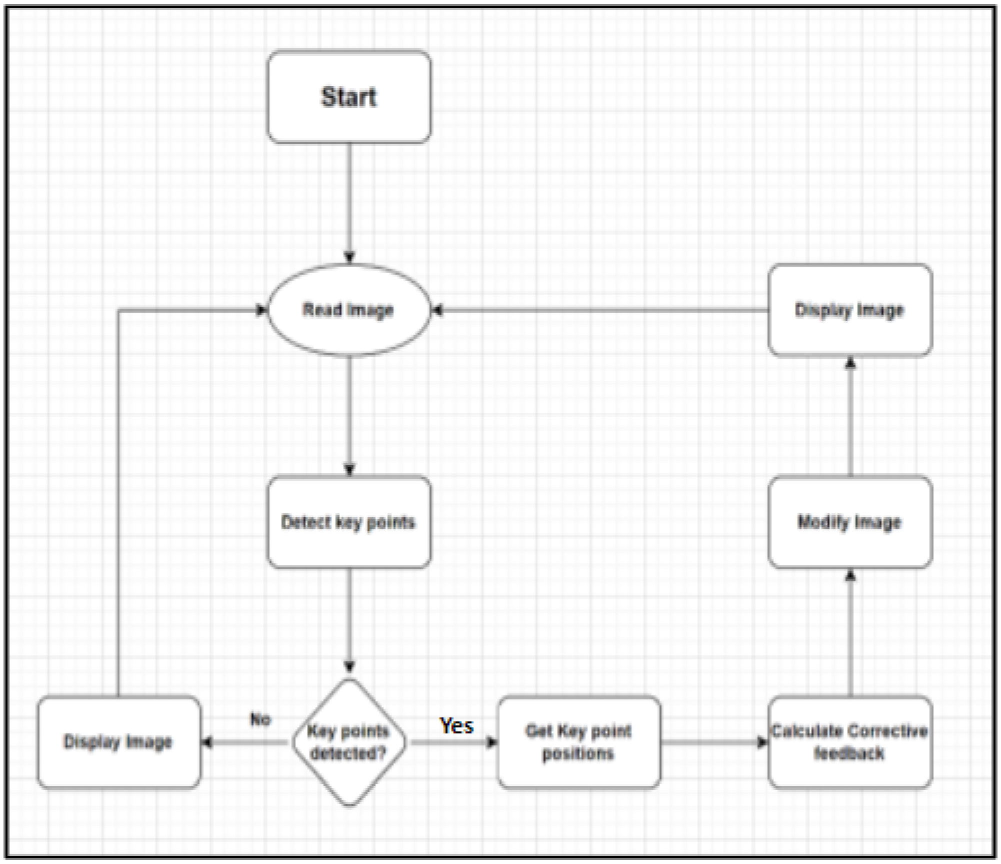


Fabricated PCB for Verification and Housed PCB

Fabricated Sleeve

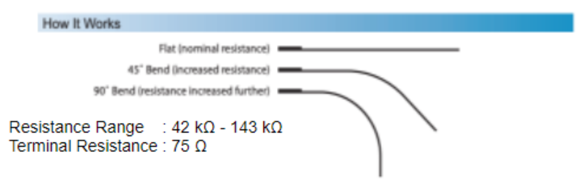


Circuit Schematic

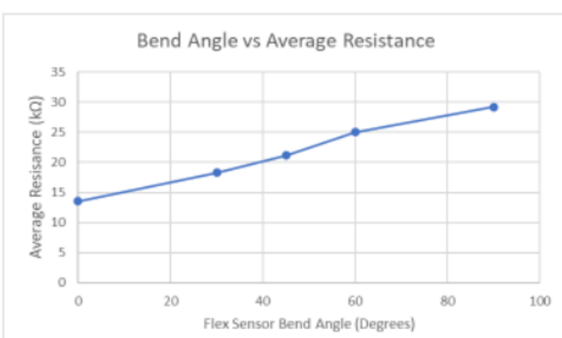


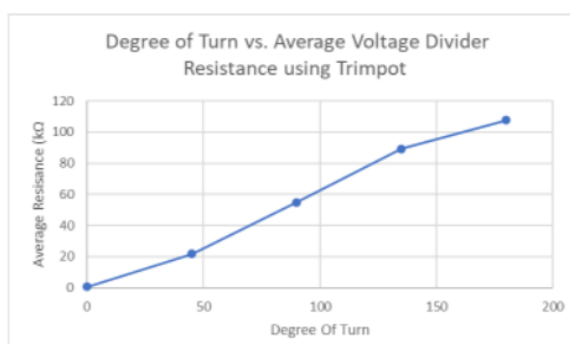
CV Unit Flowchart

Angle	Average R (kΩ)
0	13.52
30	18.29
45	21.12
60	25.02
90	29.19

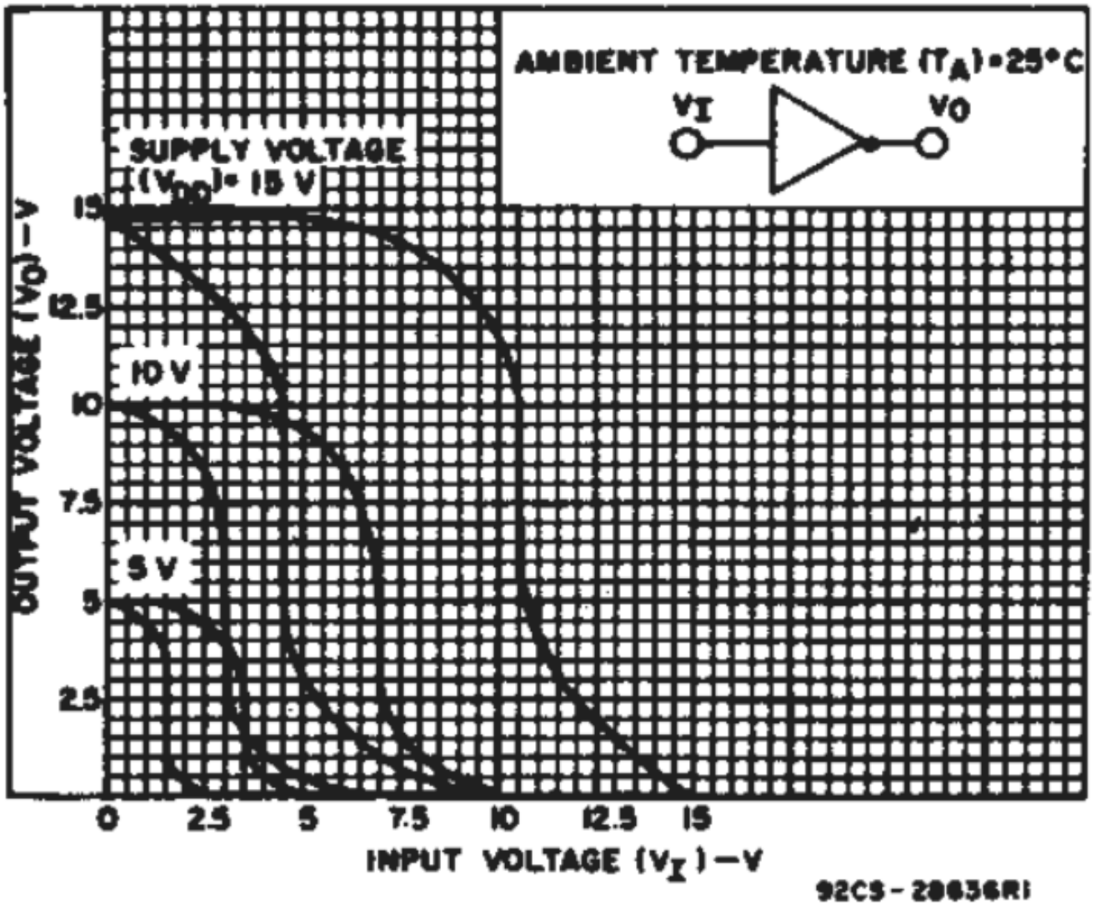


Degree of Turn with Trimpot	Average R (kΩ)
0	0.59
45	21.85
90	54.76
135	89.25
180	107.71





Resistive Flex Sensor Parameters and Plots [6]



Voltage Transfer Characteristics for CD4007BE Inverter [3]

Appendix B: Parts & Schedule

Parts

Part	Part Number	Price p. Unit	Quantity	Cost
Knee Sleeve	N/A	$12.00	2	$24.00
Flex Sensors	SEN-08606	$9.84	2	$19.68
Vibration Motor	1597-1244-ND	$1.20	2	$2.40
USB Cameras	Onn. Surf 1440P Webcam	$27.99	2	$55.98
1.5 V Battery	Energizer AA	$1.25	8	$9.99
Quad AA Battery Holder	BH-341	$2.19	2	$4.38
CMOS 555 Timer IC	TLC555CP	$0.82	2	$1.64
CMOS Inverter	CD4007BE	$0.65	2	$1.30
Operational Amplifier	LM358N	$0.93	2	$1.86
Voltage Regulator	LM317	$0.64	2	$1.28
Auxiliary RC Solder-on Components	N/A	N/A	N/A	$11.47
Total parts Cost				**$133.98**

For the auxiliary components, we needed to order at least two of each of the solder-on resistors and capacitors of varying values that are shown in the schematic, but are listed here for clarity:

Capacitors:	0.01 uF	0.1 uF	1 uF	3.3 uF	100 uF
Resistors:	470 Ω	1 kΩ x 2	100kΩ		

*****Most of these parts were stocked from the ECE supply shop, so prices may vary when ordering online due to COVID-19 and its impact on stock and shipping of electronic components.*****

Schedule

Week	Arjun	Pablo	Jason
2/28	*Begin prototyping in the lab with parts acquired from the supply shop. Debug voltage issues.*		*Research Human Pose Estimation and Cameras.*
3/7	*Finalize first PCB layout.*		*Research Human Pose Estimation.*
3/14	*Spring break.*		
3/21	*Continue prototyping with new parts acquired.*	*Part characterization and tabulation of measurements.*	*Implement Human Pose Estimation for 1 camera.*
3/28	*Finalize second PCB layout.*		*Add corrective feedback calculation to code.*
4/4	*Order solder-on parts through Digikey and acquire parts that need to be changed in the design.*	*Compile list of parts to be ordered and swapped in design, prepare some documentation in the Google Drive.*	*Make the code base modular to improve performance.*
4/11	*Solder and test the functionality of the second PCB.*	*Prepare housing unit for complete PCB.*	*Expand to all*
4/18	*Prepare materials for fabrication.*	*Debug power consumption.*	
4/25	*Solder main PCB and test. Prepare for demonstration.*	*Device fabrication and testing. Prepare for demonstration.*	*Prepare for demonstration.*
5/2	*Prepare and give the final presentation and write the final report.*		

Appendix C: Requirements and Verification Tables

Wearable Unit Subsystem

Requirement	Verification
1. Haptic feedback is provided by the coin motor at 85-90 degree flexion of the knee.	1. Voltage divider value is below the threshold for the given source. Using a ~5 V source, the threshold is ~1.4 V (from CMOS Inv Datasheet).
2. System is tuneable to the individual's ROM.	2. Using a 100 kOhm Single-Turn Potentiometer, fine-tune the voltage divider resistances at about 3:1 pot:flex resistance at maximum flexion. This is done by placing a knee on a chair or elevated surface to achieve 85-90 degree flexion, and turning the potentiometer so vibration is active.

Computer Vision Unit Subsystem

Requirement	Verification
1. All four major limbs and torso must be in the frame, both while standing and at the bottom of the motion.	1. Place a camera in front and on either side of the user. Check the body placement in frame by using the display output. Adjust the camera distances accordingly until the requirement is met.
2. Identify the 8 following pose key points standing/still and with motion: - Toes x 2 - Ankle x 2 - Knee x 2 - Hip x 2	2. Output camera feed and key points to display. First have the user stand still and visually verify that the keypoints are projected over the correct joints. Then have the user move and once again visually verify if the keypoints are still

	projected over the correct joints.
3. Identify when a user is using the incorrect form. The following constitutes incorrect form: - Front knee is past toes - Back Knee is touching the ground - Hips are asymmetric	3. Test all incorrect positions and verify the display shows incorrect form. - Do lunge a movement such that the front knee is past the front toes, an arrow should indicate to the user to move their knee back - Do lunge a movement such that the back knee is touching the floor, an arrow will point up to indicate to the user to lift the knee up - Do lunge a movement such that one hip is higher than another and two arrows will be displayed, one pointing up and the other pointing down. The up arrow indicates to the user to raise the lower hip point. The down arrow indicates to the user to lower the higher hip point
4. The latency of keypoint projection should be less than or equal to 100 ms.	4. Let ***x*** be the start time of the webcam collection. Let ***y*** be the time after doing all keypoint computations. Compute: ***Latency = y - x***

Power Subsystem

Requirement	Verification
1. Battery Voltage should not be below 10% of the defined nominal voltage.	1. DC Sources can be quickly analyzed with a multimeter before first use. If the voltage source drops below 5.4 V, it is considered dead and needs replacing.
2. Current should not exceed specified maximum current (0.19 A).	2. Connect to DC Power Supply at the desired voltage and record output

3. Each IC must be biased properly.	characteristics, current does not exceed 190 mA. 3. With the exception of the 555 Timer, all ICs are connected to the power source, and the timer is fed with the output of the inverter. The outputs are verified with an oscilloscope after PCB fabrication and soldering.

User Input Subsystem

Requirement	Verification
1. The user must attempt the body-weight lunge to completion.	1. The device verifies accomplishment of ROM and the software verifies body alignment. This is done physically by the user when their quadriceps are perpendicular to their shins.

User Output Subsystem

Requirement	Verification
1. Haptic feedback must be provided by the device.	1. The user should feel haptic pulses from the coin motor when achieving the 85-90 degree ROM.
2. The user should be able to see the three camera angles marked up with the key alignment points.	2. The user should be able to see their motion within the specified latency in the CV subsystem.