The Gait Coach

Jeffrey A. Kagle, EV Morisseau, and Daniel Garcia

***Abstract*— Haptic feedback devices offer promising avenues for gait rehabilitation, yet few studies have systematically compared different feedback types on both user perception and gait performance. This work presents The Gait Coach, a wearable system capable of delivering vibrotactile, skin-stretch, poke, and auditory feedback in a metronomic pattern, while simultaneously monitoring heel-strike timing using an inertial measurement unit. A study with three participants evaluated each feedback for gait synchronization and subjective experience, including comfort, detectability, and perceived matching accuracy. Results indicate that vibrotactile feedback is the most effective haptic feedback to replace auditory feedback in gait synchronization. However, auditory feedback was consistently rated as the most comfortable and intuitive. Skin-stretch and poke modalities were generally less comfortable and more confusing for participants. These findings highlight a trade-off between performance-driven and user-centered outcomes in rehabilitative gait systems, suggesting that vibrotactile or hybrid feedback may be optimal for applications prioritizing cadence training, while auditory feedback may be preferable for comfort-focused interventions.**

I. Introduction

There has been growing interest in developing haptic feedback devices to assist gait realignment following hemiparesis or major surgery[1]. However, most existing research has focused primarily on the engineering design[2] of these systems rather than understanding how different forms of haptic feedback influence gait improvement. Current devices overwhelmingly rely on visual, audial and vibration-based cues[3] because they are simple to implement, yet few studies have systematically explored alternative haptic modalities or analyzed how these different feedback types affect users' perception and gait performance. The limited studies that incorporate novel haptic mechanisms often evaluate their effectiveness indirectly—through metrics like knee adduction moment (KAM) reduction[8], peak thigh extension (PTE)[6], and foot progression angle (FPA)[9] —without isolating the feedback type as an independent variable. Moreover, while several meta-analyses discuss theoretical differences between haptic modalities[4][5], few have combined this analysis with controlled hardware testing and human trials.

To address this gap, our project introduces a haptic feedback system capable of delivering three distinct feedback modalities, enabling direct comparison of how each influences both the subjective experience (pleasantness, detectability, comfort) and objective gait outcomes. By systematically studying how different feedback types affect gait speed matching and perception, this work aims to provide a foundational framework for selecting and optimizing haptic feedback mechanisms in rehabilitative gait devices—bridging the current divide between design innovation and empirical validation.

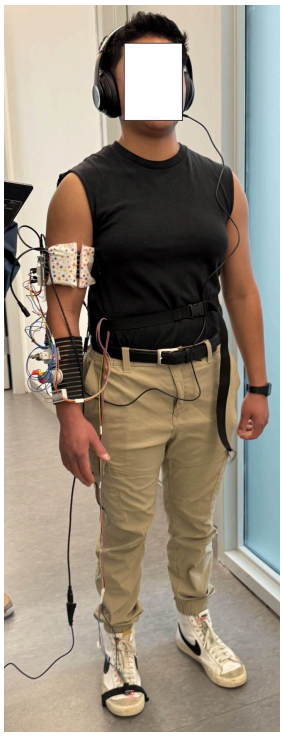


Figure 1. Participant with Gait Coach fully harnessed

II. Methodology

A. Hardware Design Methodology

To accomplish this we set out to create a device that would be able to reliably deliver 4 types of feedback: vibrotactile, poke, skin-stretch, and auditory. Vibrotactile, poke, and skin-stretch were chosen as they are common methods of tactile stimulation, therefore we tested which method was best for changing the participants' gait cycle. Auditory stimulation was chosen as a control feedback as null feedback would not be possible for our study. Additionally, auditory feedback is the one of the most commonly used feedbacks in gait rehabilitation and has shown to be reliable. Thus a non-tactile haptic feedback is used as a control to best have a comparison of each tactile feedback to alternatives. These 4 modalities were chosen to be delivered in a metronomic pattern at about 120 beats per minute which can be directly correlated to steps per minute (SPM).

Our device would also have to measure when heel strike occurs in the gait cycle to determine how well a person can match their walking to a metronomic haptic feedback. To do this we decided to use an Inertial Measurement Unit (IMU) placed on the foot to determine when a large downward to upward acceleration change occurs, showing that a heel strike has occurred. We then developed an algorithm that

[1]

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would take the timing of the IMU and match this to the SPM given by the haptic feedback. To compensate for only having one IMU placed at only one foot we divided the SPM by two to determine when alignment was reached. This would then display to the serial monitor and output how long it took for a person to match the metronomic feedback.

For the vibrotactile stimulation modality, we used an Eccentric Rotating Mass (ERM) motor driven by a NPN transistor to safely interface the motor with our Hapkit board. We powered this ERM through the board's 3.3v pin and added a flyback diode across the motor terminals to protect the microcontroller from voltage spikes. A similar approach was used to implement the poke mechanism as a solenoid was attached to a different transistor circuit, however the solenoid due to its power consumption required a separate 12V power source. For the third modality - skin stretch, we used a DC rotary motor that had an attachment on its shaft to interface with human skin. This attachment would be in contact with the skin at all times and move back and forth to induce a stretching sensation. The motor was driven using the Hapkit board's onboard motor driver which allowed for bidirectional control. The audio feedback used a female audio jack with solderless screw terminals to play audio through noise cancelling headphones.

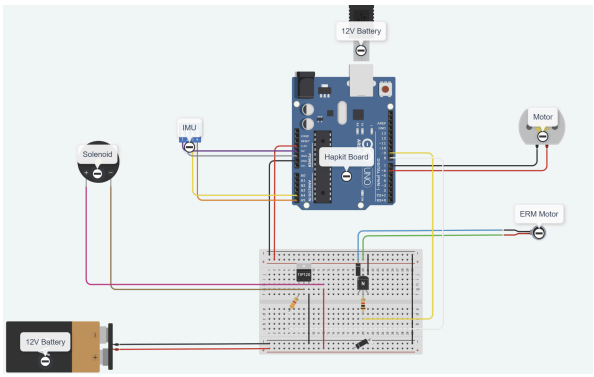


Figure 2. Complete Circuit Diagram

Three major subassemblies were made: a forearm band held our three tactile haptic feedback devices so that they had proper skin contact. This placement was chosen as it was easiest to implement and would not affect perception[7]. The upper arm band held our battery, hapboard, and protoboard that helped the two transistor circuits that controlled the ERM motor and solenoid. The shoe strap held our IMU to the center top of the shoe to detect our heel strikes. All electrical components of our subassemblies were attached with 30 AWG wire.

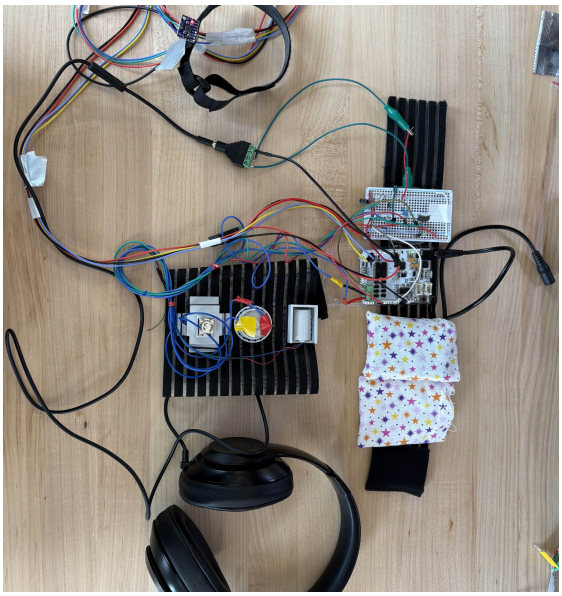


Figure 3: Final Assembly of Gait Coach with the IMU strap, haptic forearm band (center), upper arm band (center right), and headphones (bottom center)

B. Software Methodology

The software for this device was developed in the Arduino IDE platform in C++ and runs on the Hapkit microcontroller board. Each mode's program is responsible for generating a metronomic timed haptic feedback that matches the 120 SPM that we have set to be the datum matching speed. All of these modalities were set to an intensity that we felt was comfortable, and noticeable for the study.

The heel-strike detection algorithm operates by continuously sampling the accelerometer data from the IMU and computing the magnitude of acceleration to obtain an orientation-independent signal. This magnitude is monitored for sharp increases corresponding to heel-strike impacts. A heel-strike is registered on the rising edge when the acceleration magnitude exceeds a predefined threshold, ensuring it is not affected by gradual motion changes. To prevent multiple detections from a single step, a refractory cooldown period is used before another event can be registered. The timestamps of successive heel strikes are then used to estimate step timing and cadence by computing the interval between detected events.

A snippet of the script for the vibration motor is shown in Fig.#. This script controls the ERM using pulse-width modulation (PWM) to produce the rhythmic pattern, by remaining on for 300 ms, then turning off for 200 ms. This on/off cycle repeats continuously until it matches the corresponding pattern through the IMU.

```ino
// Code for vibration feedback - V1
const int motorPin = 9;
// Adjustable vibration intensity (0-255)
const int pwmStrength = 180;// Vibration Strength
// Timing
const int onTimeMs  = 300;// 0.3 seconds ON
const int offTimeMs = 200;// 0.2 seconds OFF

void setup() {
  pinMode(motorPin, OUTPUT);
  analogWrite(motorPin, 0);// Motor off at start

  Serial.begin(9600);
  Serial.println("Vibration motor running: 0.3s ON, 0.2s OFF (120 BPM)");
}

void loop() {
  // Motor ON
  analogWrite(motorPin, pwmStrength);
  Serial.println("ON");
  delay(onTimeMs);

  // Motor OFF
  analogWrite(motorPin, 0);
  Serial.println("OFF");
  delay(offTimeMs);
}
```

Figure 4: Code Snippet for Vibration Modality

As shown in Fig. # This script controls the DC motor used for our skin stretch modality using the Hapkit motor driver by setting both the motor speed/strength and direction through digital and PWM. Similarly to the pattern induced by our ERM, this motor is configured to match the SPM through a "forward" and "reverse" motion to induce a skin stretching sensation. This cycle is also repeated per trial until alignment has reached.

```ino
const int dcPwmPin = 5;     // PWM speed pin for DC motor (Motor 1)
const int dcDirPin = 8;     // Direction pin for DC motor (Motor 1)

int motorSpeed = 200;       // 0-255: strength/speed of DC motor
int forwardTime = 150;      // 0.15 seconds ON in forward direction
int reverseTime = 150;      // 0.15 seconds ON in reverse direction
int offTime = 200;          // 0.2 seconds OFF between cycles

void setup() {
  pinMode(dcPwmPin, OUTPUT);
  pinMode(dcDirPin, OUTPUT);

  // Start motor OFF
  analogWrite(dcPwmPin, 0);
  digitalWrite(dcDirPin, LOW);

  Serial.begin(9600);
  Serial.println("DC motor back-and-forth started...");
}

void loop() {

  // For
  Serial.println("FORWARD");
  digitalWrite(dcDirPin, HIGH);// forward direction
  analogWrite(dcPwmPin, motorSpeed);
  delay(forwardTime);

  // Rev
  Serial.println("REVERSE");
  digitalWrite(dcDirPin, LOW);// reverse direction
  analogWrite(dcPwmPin, motorSpeed);
  delay(reverseTime);

  // OFF (0.2s)
  Serial.println("OFF");
  analogWrite(dcPwmPin, 0);// motor OFF
  delay(offTime);

  // Loop repeats forever
}
```

Figure 5: Code Snippet for Skin Stretch Modality

Lastly, similarly to our previous two modalities, the solenoid is configured to actuate in an on/off pattern that matches the set SPM, as written in Fig.#The solenoid is set to HIGH to apply force to the user's skin. When set LOW, the solenoid disengages. This again remains on for 300 ms and turns off for 200 ms, per cycle.

```ino
const uint8_t solenoidPin = 3;

void setup() {
  pinMode(solenoidPin, OUTPUT);
  digitalWrite(solenoidPin, LOW);// ensure it starts off
}

void loop() {
  // Turn solenoid ON
  digitalWrite(solenoidPin, HIGH);
  delay(2000);

  // Turn solenoid OFF
  digitalWrite(solenoidPin, LOW);
  delay(2000);
}
```

Figure 6: Code Snippet for Poke Modality

C. Study Methodology

I. Experimental set-up

Three able-bodied participants (3 males; ages 22-27) participated in the study. Participants were instructed to wear the forearm band containing the haptic feedback devices on their right forearm area, the upper arm band containing the electronics on the upper right arm, the shoe strap holding an IMU on the tip of their right foot, and lastly noise cancelling headphones. These devices were worn throughout the entirety of the study.

Three trials were completed for each feedback type for a total of 12 trials. The order in which participants encountered trials was randomized per participant. Each trial consisted of a 30 meter (m) walking test with metronomic feedback delivered at the same preset walking speed: 120 SPM. Participants were not made aware what the walking speed was numerically, nor were told that the speed remained the same across trials. The 30 m walking test was conducted in an indoor hallway, with smooth floor conditions. Participants were tasked with matching each step to each metronomic pulse they experienced as best as possible.

From the IMU on the participant's right foot, we collected participant walk speed data to assess in seconds (s) the time it took each participant to match the 120 SPM walking speed per trial. In order for the IMU to recognize the speed as matched, the walking speed must have been matched for 6 consecutive seconds. If the walking speed was not matched within the 30 m distance, no time to match value was recorded. Additionally, we determined if a participant favored feedback mode using a 7-point likert scale (0 being low and 7 being high) administered after each trial to rank comfort, level of perception, their own perceived matching accuracy, and leave any open ended comments as desired. Lastly, we also completed a short participant interview after all trials were completed to directly ask participants about the feedback modes overall, and allow participants to leave any remaining comments.

II. Procedure

In the introduction stage of the study, participants were assisted in donning the devices and the details of the walking task were explained to them. Subsequently, they were guided through each feedback type and allowed to experience each in a random order. They were invited to practice the walking task with each feedback for about 30-60 seconds to

familiarize themselves with the task and feedback sensations.

Participants began each trial at one end of the 30 m distance marked with tape. Prior to each trial participants are not told which feedback mode they will experience. Participants were verbally told when to begin walking. Five seconds after beginning to walk, the trial feedback begins, and participants attempt to match their steps to the feedback as instructed. Participants will continue walking until reaching the end of the 30 m distance, and a researcher will immediately stop the feedback. Participants are then given an iPad to complete the Likert scale survey via google form. Once finished, participants are set to begin the next trial. This process is completed 12 times, once for each feedback trial.

After all trials were completed, participants were assisted in doffing the devices and were taken to a small meeting room to ask them questions about the comfort of the feedback, their performance, and preferred feedback type. Participants are also invited to leave any further comments as desired.

D. Data Analysis Methodology

All participant IMU recorded matching times were compiled and grouped by feedback type. A two-sided, unpaired Welch's t-test was conducted separately between the vibrotactile and skin-stretch feedback types and the audio feedback as it is our control. We completed this type of t-test as it would provide us a measure of how statistically different the means of the two compared groups are and does not assume the variances are equal which we do not have. Furthermore, because we randomized the feedback trials, measured results are not connected or paired, so we opted for an unpaired t-test. Comparing the t-test p-value outputs, we wanted to find the test with the largest p-value, as this indicates a smaller statistical difference between that haptic feedback type and the control feedback (audio).

For the poke feedback, due to device malfunctions, only one successful IMU match time was collected. As a result, a two-sided, unpaired Welch's t-test cannot be completed between the poke and audio feedback. To compare if there is a statistical difference between the audio feedback values and the single poke feedback value, a one-sample t-test was conducted. This p-value cannot be compared equally to the p-values calculated by the other t-tests as they are different kinds of t-tests.

For the likert survey data, to understand which feedback mode had the highest overall scores for each survey question, we grouped the participant likert scores by question and feedback type. We then calculated the mean for each, and compared them to one another. A mean value closer to seven indicates a more positive score for that question and feedback type.

III. Results

The results of the IMU match time data analysis are presented in Figure 7. From the two two-sided, unpaired, Welch's t-tests conducted between the control feedback (audio) and the vibrotactile and skin-stretch haptic feedbacks, we calculated a p-value of 0.604 and 0.1730 respectively. Comparing these p-values to one another, it is found that the vibrotactile feedback is less statistically different to the control feedback than the skin-stretch feedback. Thus the vibrotactile feedback elicits results most similar to the control feedback and thus is best suited to replace the control feedback in gait matching rehabilitation tasks. Furthermore, visually, the vibrotactile feedback results are closer to the control feedback results than the skin-stretch feedback.

From the one-sample t-test conducted between the control feedback and poke haptic feedback, we calculated a p-value of 0.711. Due to the poke feedback analysis being completed with a different t-test, we cannot directly compare its p-value to the other t-test results. However, its high p-value suggests that further research to explore this possible relationship would prove fruitful.

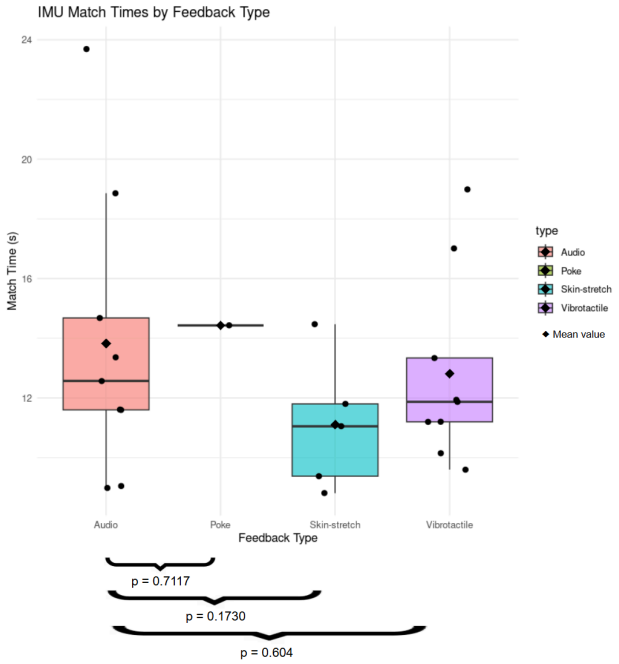


Figure 7: Plot of the raw data collected per feedback type with results from IMU match time t-tests, diamonds represent feedback data mean value

The results of the Likert survey data analysis are presented in Figure 8.

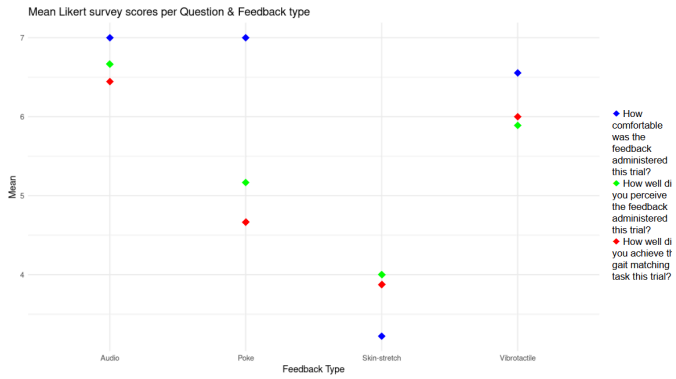


Figure 8: Plot of the mean Likert survey score per Question & Feedback type

As a final component of our study, each participant was asked to take part in a short post-study interview. In this interview, all the participants were asked the same four questions to gather additional information and feedback on their experience with the device. The following questions were asked:

1. How was the device comfortability?
2. How well do you think you did overall?
3. Which feedback type was your favorite?
4. Which feedback type was the most confusing?

TABLE I. Participant Responses

Q	Responses (Participant 1)
1	The comfortability was fine overall. “ skin stretch became uncomfortable over time”
2	Audio was the easiest to perceive but vibration was a close second. Solenoid was harder to perceive since it had “an extra layer of feedback when it retracts”
3	Audio was easiest/more intuitive, but vibration was the favorite haptic feedback.
4	The most confusing was between skin stretch and poke.

Q	Responses (Participant 2)
1	Comfortable overall. All the “straps were not tight” and comfortable.
2	Good overall, the “solenoid was the hardest" to match but the rest of the trials were easy to match.
3	Best feedback to complete the task was audio, favorite and also easy to match was vibration.
4	The most confusing and uncomfortable was skin stretch

Q	Responses (Participant 3)
1	“The device became uncomfortable as time went on”. The skin stretch modality was the most uncomfortable.
2	“Not well.” The audio and vibration were easy to match, but the other “two were hard” to match
3	“Sound helped me do it the best, but my favorite was vibration.”
4	“Skin stretch and the poke were a tie between most confusing”

In terms of comfort, perceptability, and self scored matching ability, the control feedback (audio) was consistently ranked highest. Coming in close second was the vibrotactile feedback, further corroborating our results as vibrotactile being best suited to replace auditory feedback in gait synchronization tasks. Skin-stretch was consistently ranked as the worst feedback type in terms of comfort and perception as it was extremely uncomfortable and difficult to follow.

IV. Discussion

While these results display positive inclination towards vibrotactile feedback as our conclusion, several limitations during data collection actively limited the data analysis processes we could complete, and may influence these results.

Our device has several limitations, stemming from our device code and circuit design that caused difficulty while completing these experiments. One of these is that our circuit design caused our solenoid to interfere with our microcontroller communication due to the large power draw from the battery; this can be fixed by implementing a second battery or 12V power source to the device. Another limitation is that the Arduino IDE environment that was used to collect data only allows for a small amount of serial monitor printed data to be copied for data analysis. This limited the amount of data that our results could include; this can be fixed in the future by using a different arduino environment or creating a new function that copies all data to a .txt file. Furthermore, due to the large amount of data the IMU outputs the Arduino microcontroller can easily overwhelm its data storage capabilities, thus leading to necessary code edits to wipe previous data inputs to continue functioning. By increasing the processing power of our microcontroller or isolating the IMU to a separate microcontroller this issue can be fixed.

More limitations came in the form of our hardware design. Primarily issues came in the form of wires and the IMU strap falling off due to weak connections. This caused

trials to come to a halt as the device would need to be mended. In the future, iterating on our design to have stronger connections or decrease the stress on weak points would fix these problems.

While completing our participant trials, these limitations eventually made the poke haptic feedback unusual in a walking test and trials with the poke feedback could no longer be run. As a result, we were unable to test all participants from the original planned participant pool, severely limiting the amount of data collected and analyzed. This breakdown occurred while testing our final participant, we thus were unable to test the poke haptic feedback with this one participant. This combined with difficulty copying data over from the Arduino IDE environment caused us to only have one collected IMU matching time data point for the poke feedback. With only one data point we were unable to complete a two-sided, unpaired, Welch's t-test between the poke and control feedback as planned. While we were able to complete a one-sample t-test, the p-value output of this t-test could not be compared with the other calculated p-values.

Furthermore, the difficulty copying over data from the Arduino IDE environment also caused us to possibly lose some data points for all forms of feedback. This makes it difficult for us to know if a trial failed because the participant could not match the feedback, or if data points are missing.

V. Conclusions and Future Work

Our findings indicate that vibrotactile feedback was the most effective haptic feedback to replace auditory feedback in gait synchronization, while auditory feedback was rated as the most pleasant and comfortable by participants. This distinction highlights an important design trade-off between performance-driven and user-centered outcomes in rehabilitative gait systems. Vibrotactile cues appear well suited for applications where precise cadence training and minimal visual or cognitive load are critical, whereas auditory cues may be preferable in situations where comfort, user acceptance, and reduced physical intrusion are prioritized. Accordingly, future haptic feedback devices targeting gait modification should strategically prioritize vibrotactile, auditory, or hybrid feedback approaches based on the specific clinical goals, environmental constraints, and user populations they are intending to serve.

To validate our design and conclusions a larger study should be done with more participants over more trials to confirm our data and findings. The participant pool was chosen from a group of healthy college-aged students which limits our data pool further. Future studies should be done with a more diverse range of participants of different ages and anthropometric ranges to confirm that results do not only apply to one group of individuals. This could also include individuals with lower body disabilities to confirm our data matches with those with impairments to their gait. Furthermore, recompleting the study with improvements to the limitations mentioned previously would greatly validate our data and findings.

The Gait Coach device can improve in many ways, including miniaturization, fitting, and streamlining. Our current device focused on using cheaper, off-the-shelf parts. By making smaller, custom parts the device size and weight could decrease thus miniaturizing our device. This also applies to our forearm, arm, and foot straps as yet again, simplicity was emphasized so modified off-the-shelf straps were used to fit onto each person which could prove difficult for people with differing arm or foot sizes. Thus working on how devices can fit different persons would improve the comfort and effectiveness. With all of this by streamlining our device and improving wire management, number of parts and combining components we could decrease the complexity of our device which would allow easier implementation of our device for future studies and decrease the cost.

Appendix

TABLE II. Gait Coach Components

Component	Number of Components	Unit Price
MPU6050 IMU	1	$12.95
Hapkit Board	1	$30.00
12V DC Motor	1	$7.27
12V Solenoid	1	$7.49
2N2222 Transistor	1	$0.17
TIP120 Transistor	1	$1.10
1kΩ Resistor	1	$0.10
3.3kΩ Resistor	1	$0.13
1N4001 Diode	2	$0.19
Protoboard	1	$1.50
30AWG wire	To Anthropometric Constraints	$10.00
12V Rechargeable Battery	1	$20.99
Nylon/Polyester Band	To Anthropometric Constraints	$9.99

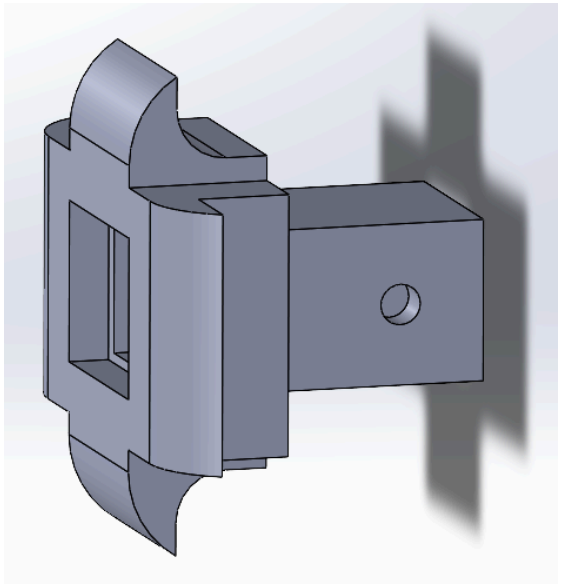


Figure 9. Render of Solenoid Housing

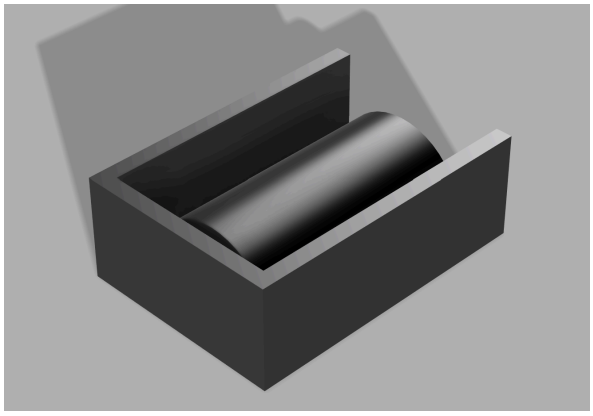


Figure 10. Render of ERM Motor Housing

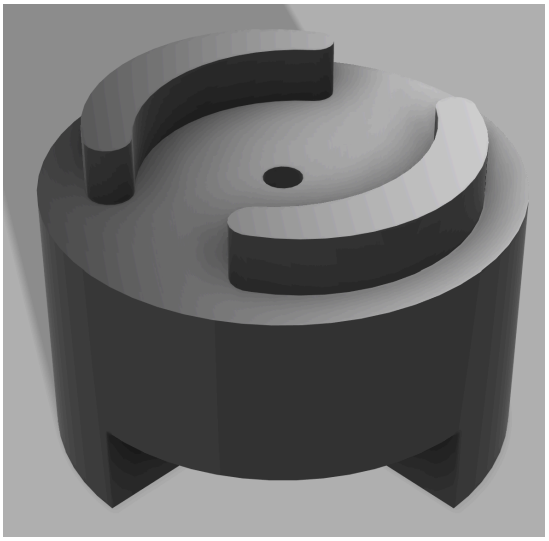


Figure 11. Render of Skin-Stretch End Effector

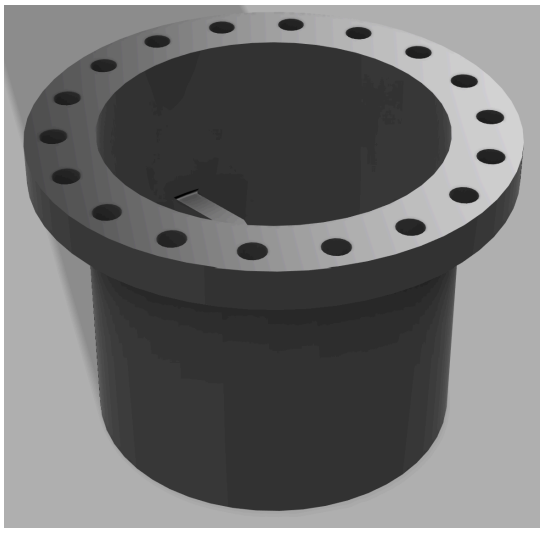


Figure 12. Render of DC Motor Housing

Acknowledgments

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Generative AI (ChatGPT) was used for general code debugging and R code documentation/library search purposes

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Files

- *Final_Code_v7.ino*
  - Final Version of Code to be run on Hapkit Board
- *Gait coach components.gsheet*
  - List of Components
  - Number of components used
  - Components approximate price
- *The Gait Coach Data analysis.R*
  - R-code of data analysis for participant trials
- *Skin Stretch Mech.stl*
  - Model of Skin-Stretch End Effector
- *Attach to belt skin 2.0 real.stl*
  - Model of DC Motor Housing
- *ERM motor holder.stl*
  - Model of ERM Motor housing
- *Final Solenoid Holder.stl*
  - Model of Solenoid Housing