Design of an auditory cueing system for improving Freezing of Gait in patients with Parkinson's Disease

E164 Final Project Deliverable

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1. BACKGROUND

Parkinson's Disease (PD) is a central nervous system disorder that is primarily characterized by motor impairments such as tremors, bradykinesia (slowed movement), stiffness of muscles, poor posture, and Freezing of Gait (FoG) [1]. These are the result of progressive loss of neurons in substantia nigra, a small region in the midbrain that produces dopamine. Dopamine is a neurotransmitter that is essential for smooth and coordinated movements [2]. Research has shown that people with PD lose 60 to 80% of cells that produce dopamine, thus causing rigidity and involuntary/delayed movement [3]. In addition to these symptoms, people suffering from PD also experience loss of the nerve endings that produce norepinephrine. This neurotransmitter increases alertness and controls the body's blood pressure during times of stress. Therefore, a lack of norepinephrine causes symptoms such as blood pressure changes, fatigue, anxiety, and more. Currently, although there is no cure for PD, there are medications available to help patients alleviate their motor (and non-motor) symptoms. Dopamine precursors to increase dopamine level in the brain, or other drugs that mimic its function are prescribed [3]. Exercise and physical therapy can help alleviate symptoms as well, and assistive devices that promote more controlled movement are also helpful.

One of the most serious symptoms of PD is Freezing of Gait (FoG) [5]. FoG is typically defined as a brief inability to move the feet forward despite intending to walk, often appearing as shuffling, trembling, or simply standing still. These episodes commonly occur when starting to walk or when approaching boundaries such as doorways or crowded spaces [4]. Lesion network mapping has linked several brain regions, including the parasagittal frontal area, left postcentral gyrus, and brainstem, to FoG [6]. Each of these areas plays a key role in coordinating the complex motor and sensory signals required for turning, walking, and navigating around obstacles. Because these regions are implicated in FoG, neuromodulation strategies (most notably deep brain stimulation) that deliver stimuli have been explored as possible treatments. However, no conclusive evidence has yet been found regarding their efficacy [4].

The three primary forms of treatment for FoG are medications (such as levodopa [7]), physical therapy (such as gait training on a treadmill [8]), and external sensory cues. The team's design primarily focuses on the latter, as it can be implemented using a device. Prior work done in this solution space is explained here.

Visual cues are popularly used to help PD patients take the next step, with the most popular form being laser canes. These canes project a straight line approximately a stride-length in front of the individual, which works to trigger the visual-motor pathway in the brain and help the user initiate stepping movements. Research has shown that this laser cane cueing solution helps improve right and left stride length, step length, velocity of movement, and rotation time as compared to walking without it [9]. Some limitations with this visual cue is that it becomes quite ineffective in broad daylight, as the laser could be difficult to see. The stride length adjustability is also difficult to implement into the laser, as it has to be modified mechanically for each user. This solution also promotes the user to look down at the floor rather than up, which can hinder full gait progress down the line due to promoting bad posture.

Haptic cueing techniques are also used by PD patients. Vibrating socks were used to deliver these tactile cues, as they had the benefit of not being noticeable to people around the user [10]. Research has shown that this has helped FoG in individuals, and that a personalized approach is needed for the solution to be most effective. Another way this cue was implemented was in wearable haptic anklets. This device delivered "personalized suprathreshold alternating exteroceptive stimulation," which essentially functioned as a walking pacemaker [11]. This way of cueing was shown to significantly improve walking abilities such as velocity and stride variance and reducing the duration of FoG episodes. While these haptic cues do not limit the patients' interaction with the outside environment like the previous cueing mechanisms described, limitations exist in their personalization and delivery, as skin sensitivity varies between individuals and effectiveness can be impaired based on PD patients having a considerable amount of subcutaneous fat.

Auditory cues are also used by PD patients to help the brain initiate stepping movements. These are primarily implemented as metronome beats which can be set to the user's stride pace. Research has shown that an effective method for auditory cueing is setting the metronome to 10% above the patients' normal walking cadence [12]. It has been shown to increase the speed of gait initiation, muscle activation, and walking speed in general [12]. However, this method of cueing is not perfect either, with possible limitations existing in its implementation. For example, the metronome being too loud or being heard through headphones can overpower and distract the user from receiving other auditory cues around them. Upon research, the team concluded that compared to visual and haptic cueing, auditory cueing is not as popularly implemented. Therefore, in order to test its validity and limitations, the team focused on this cueing mechanism.

2. DESIGN OVERVIEW

In order to help improve FoG in individuals with PD, the team is designing and developing an auditory cueing device. This device, which consists primarily of a metronome circuit enclosed in a housing, is designed to either attach to existing canes or the individual's clothing. It provides adaptable metronome beats which can be set to the user's stride pace and increased as the patient's walking cadence improves. Table 1 contains the objectives, constraints, and functions the team has identified in order to develop a successful design.

Objectives	Constraints	Functions
• Be durable so it does not require frequent battery changes • Be user-friendly for intersecting with cueing knobs • Be lightweight • Be small in size • Be customizable	• Final prototype must be less than $105 • Final prototype must not be too heavy (less than 3 pounds) such that it impairs user's movement	• Has adjustable metronome for FOG recovery • Produce audible cues that the patient can respond to without inhibiting natural cues around them • Improve gait stability in patients with Parkinson's Disease • Contains a detachable cueing system

Table 1. Objectives, constraints, and functions for the cueing device.

2.1 ELECTRONICS DESIGN

The metronome circuit was designed off the basic principle of a 555 timer circuit, as it is simple and can be used to produce timely beats. The schematic reproduced in figure 1 was the starting point of the design [13].

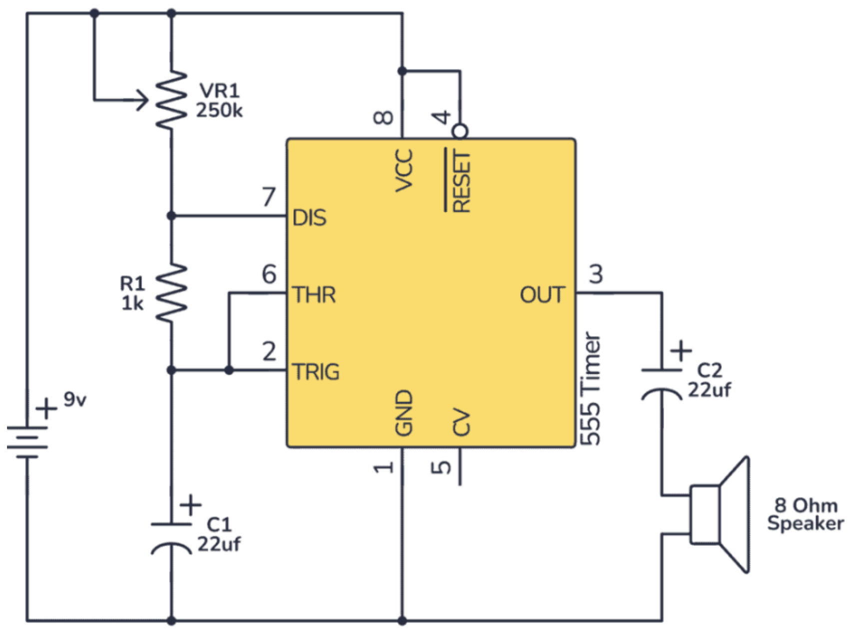

Fig 1. 555 timer schematic

The metronome circuit's adjustability relied on the potentiometer VR1, intended to be 250 kΩ. The period of the 555 timer signal that creates the sound can be calculated using Equation 1, where R_{pot} is the resistance of the potentiometer, R_1 is the 1kOhm resistor, C is the 22 uF capacitor, and T is the period in seconds at the center/average value of the potentiometer.

$$T = 0.693 * (R_{pot} + 2R_1) * C \qquad \text{(Eq. 1)}$$

The period of the 250k potentiometer equates to about 3.84 seconds, or one beep every 3.84 seconds. However, due to the constraints of the equipment in the lab, a 300kOhm potentiometer was used for the initial prototype. Following the same equation, the period for this potentiometer is about one beep every 4.60 seconds. The average age of an individual with Parkinson's is about 60 years old [14]. The average walking speed of adults around the age of 60 is between 1.24 and 1.43 meters per second [15], which translates to about a step every 0.8 seconds. This means that raising the potentiometer resistance pulls the cadence farther away from a realistic stepping speed. Given that the target user will probably move slower than this average speed, having an average range near one beat every 3 seconds is more desirable for the cueing device. As such, in the final design, a 250kOhm potentiometer was ordered, which returns the average cadence to 3.84 seconds.

The circuit was first prototyped on a large breadboard as seen in figure 2 and used large electrolytic capacitors with much higher voltage ratings than required for this application. The circuit was remade on the smaller breadboard shown in figure 3 to make it easier to use and house, and used capacitors with smaller, more realistic voltage ratings.

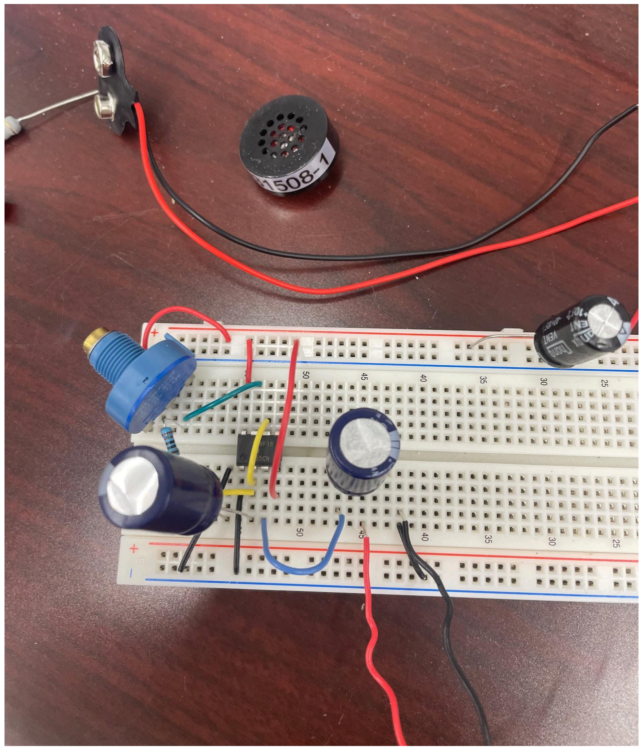

Figure 2. Initial breadboarded circuit

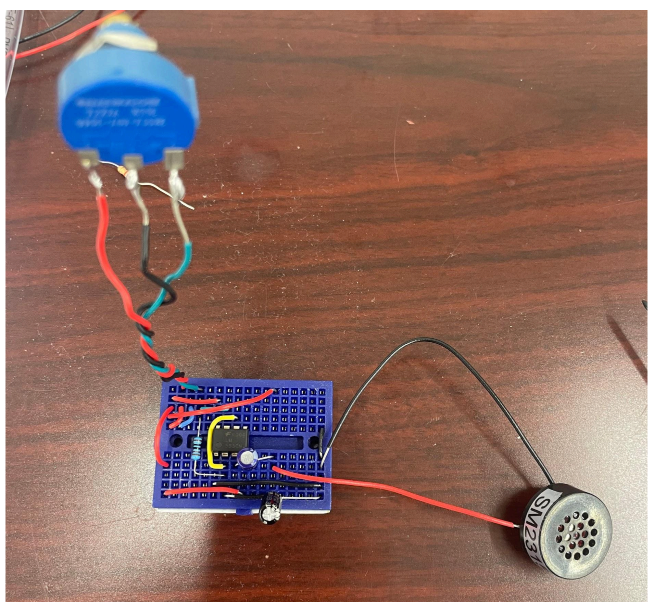

Figure 3. Smaller breadboard circuit for initial prototype

In order to provide a robust and reliable platform for the metronome circuit, the team decided to implement the electronics on a PCB, which is shown in figure 4. The software KiCad was used to translate the prototyped circuit onto a PCB, the necessary components were ordered from DigiKey. After determining the compact, desired dimensions of the circuit, it was fully designed on KiCad. The team ordered a blank PCB from JLCPCB and decided to solder the components by hand, as manufacturing time and cost would increase when ordering a fully-soldered board.

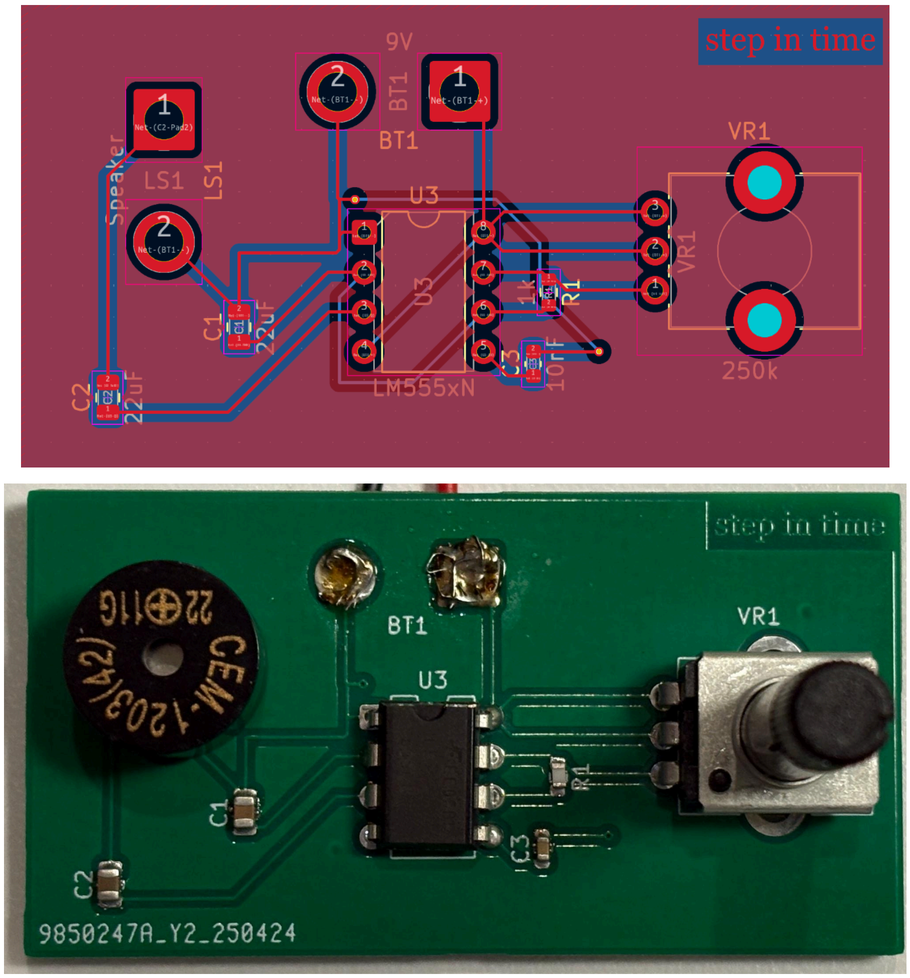

Fig 4. Custom metronome circuit PCB schematic (top) and assembled PCB (bottom)

When assembled, the circuit on the PCB worked as intended, producing signals at varying speeds when the potentiometer knob was twisted. As detailed in section 2.2, a casing was designed for the PCB such that it was secure and did not shake or vibrate when the user was walking.. The container design ensured easy access to the potentiometer such that modifying the cadence was effortless and straightforward. In addition, the electronic housing design allowed for the speaker to be outside the container, making it easier for users to hear the metronome and ensure they followed the cadence.

2.2 MECHANICAL DESIGN

The mechanical component of the project was designed to securely house the metronome circuit components, provide ease of use, and create a more compact storage so users did not need to hold the circuit. The casing needed to contain the metronome PCB which measured 2.19 in x 1.17 in x 0.34 in, as well as a 9V battery which had an added height of 0.67 in. Extra space was added to each measurement in order to provide sufficient clearance for the circuit board and facilitate straightforward insertion and removal. This resulted in internal box dimensions of 2.25 in x 1.2 in x 1.22 in with a uniform box thickness of 0.15 in.

While material selection is pending further development, preliminary considerations suggest a lightweight, durable, and non-conductive material. Options that satisfy this include specific types of wood like basswood or plastics such as ABS.

A prototype was initially developed to fit a commercial circuit originally intended to be purchased for the project. It was also designed to include a snap-fit attachment on a cane located at the back of the box. This initial design, which is shown in figure 5, was not continued as the decision was made to build our own 555 Timer and PCB board instead.

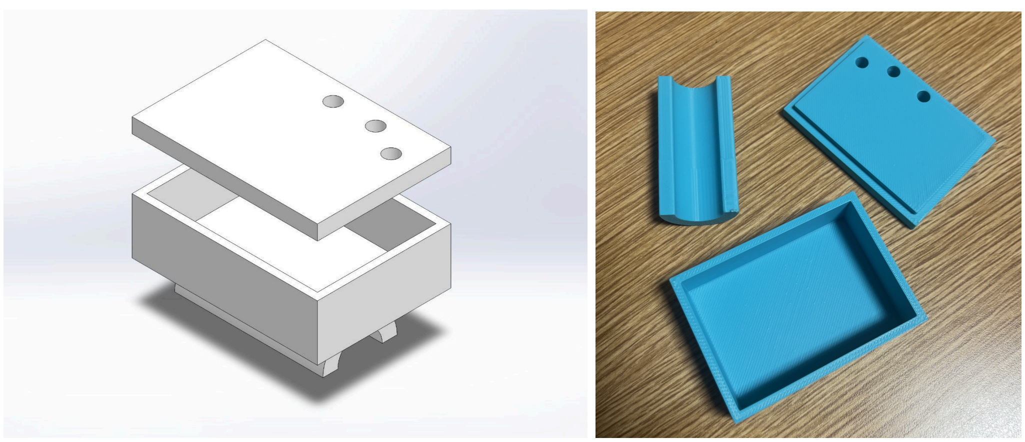

Fig 5: First Prototype of mechanical casing

The holes in the first prototype accommodated volume and speed knobs present on the original online circuit the team was following. The design was later revised with dimensions specific to the new prototype, which was a 555 timer on the small breadboard. The team decided to remove the volume knob for the final design due to difficulties in implementing the speaker. A belt clip attachment was also included so the patient could wear the device on their belt rather than attaching it to a walking device. This design and drawing, which were for the circuit on the small breadboard, are shown in figure 6 and 7, respectively.

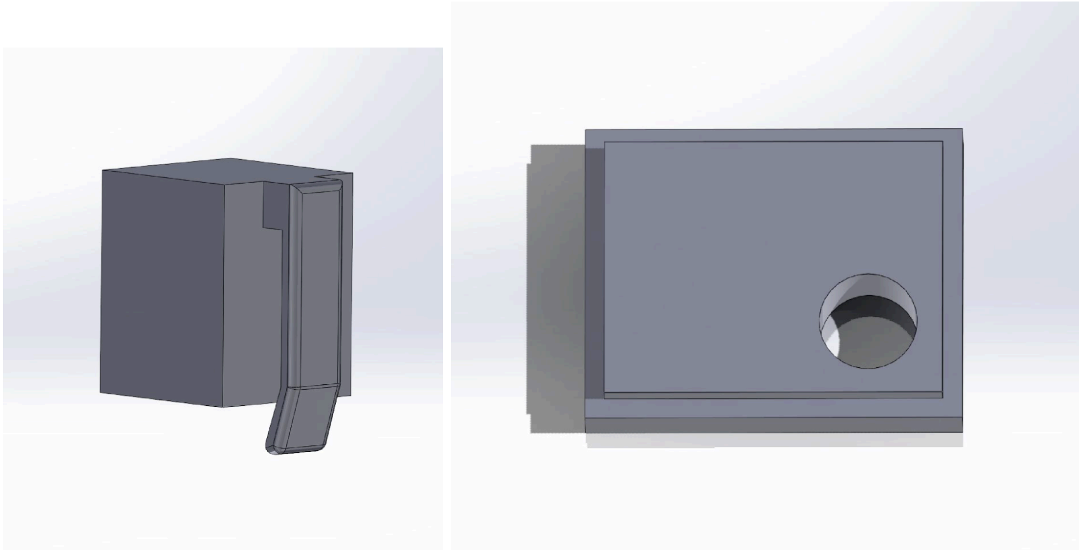

Fig 6: Dimetric view (left) and bottom view (right) of the second prototype's main housing

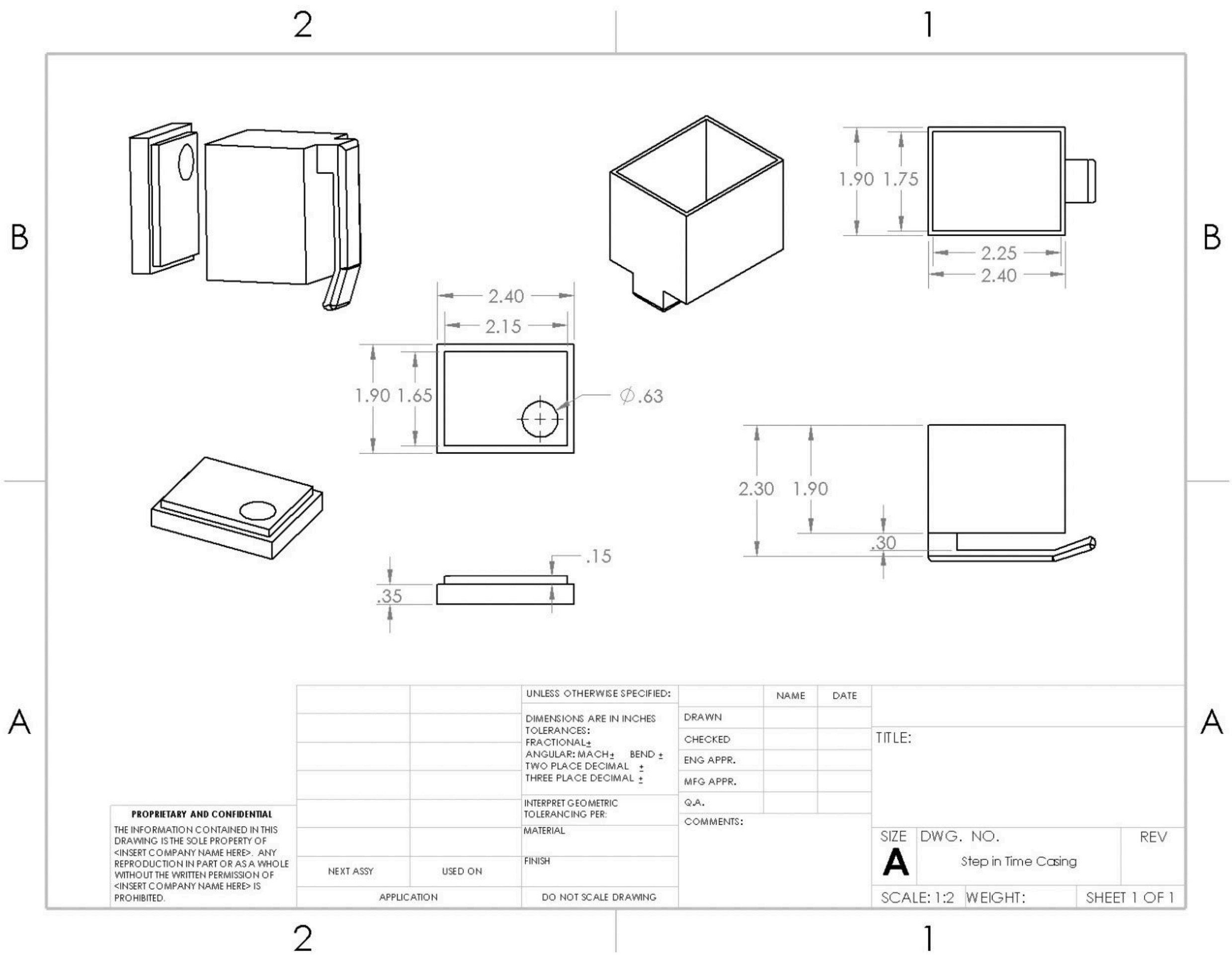

Fig 7: Drawing and measurements of prototype 2 assembly

Fig 8: 3D printed prototype with spongebob decor (on it's own and attached to participant)

The participants found the belt clip intuitive and easily attached the device onto themselves. However, three major issues arose during testing. The first was that the lid of the casing was not a perfect fit on the body of the casing so a small magnet was attached to the inside and outside of the casing to make it better toleranced and have an added connection between the two pieces. Another problem was that the potentiometer barely stuck out of the hole so users needed to stick their finger nail in in order to modulate the timing. Lastly, when the casing was fully closed it was difficult to hear the metronome. The team took these issues into consideration for the final mechanical casing prototype, which was aimed to house the PCB. The new design and drawing are seen in figures 9 and 10, respectively.

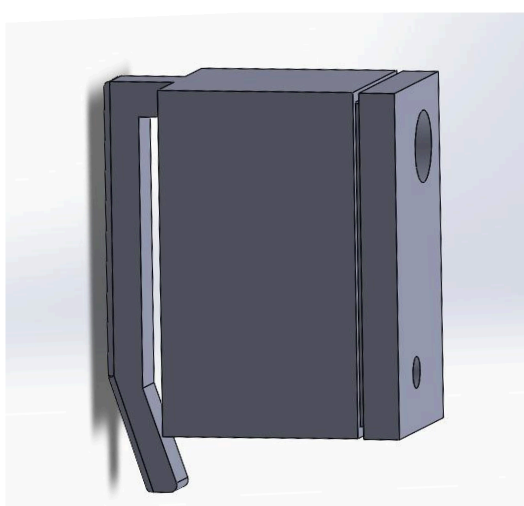

Fig 9: Side view of the third prototype's housing

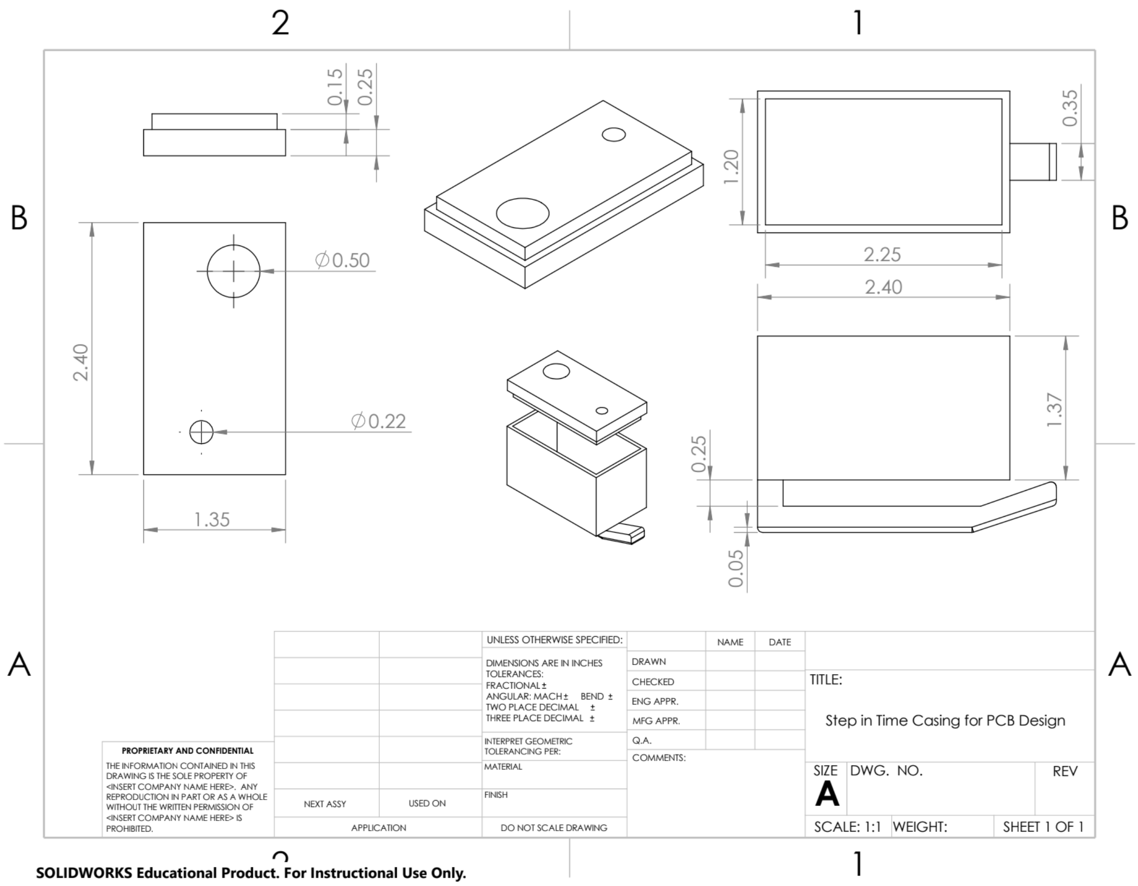

Fig 10: Drawing and measurements of prototype assembly

Although the team was unable to test the final prototype for the PCB layout through 3D printing, it was designed on Solidworks and the tolerances were validated using calipers. This time, the lid was tightly toleranced to prevent slippage. Also, based on the new size of the potentiometer part on the PCB, 0.25 inches of the potentiometer knob was designed to stick out from the casing to make it easier to access. Additionally, a second hole was added for the speaker in order to make hearing the metronome clicks easier.

The mechanical casing effectively addressed the portability and ease of use of the circuit, particularly through the inclusion of a belt clip. The belt clip was carefully designed with a curved end to prevent the casing from slipping off the patient due to the weight of the contained circuit and battery. Additionally, the holes in the lid of the casing were measured precisely to allow the potentiometer knob to fit securely outside of the casing and allow sound from the speaker to propagate.

3. TESTING RESULTS & DISCUSSION

3.1 USER TESTING PLAN

The user testing aims to evaluate the effectiveness of a wearable attachment containing a 555 Timer (metronome) circuit designed for gait synchronization. The testing assesses how accurately participants match their walking pace to the metronome, their multitasking ability while using the device, and the overall ease-of-use in various scenarios, including attachment to the body or walking aids. Although initial testing does not involve Parkinson's patients, the collected data establishes baseline metrics useful for future predictive simulations addressing Freezing of Gait (FoG) in Parkinson's patients.

The study used a small sample group of approximately 3 to 5 healthy individuals. Testing took place on a 15-foot flat walking path located outdoors on the Claremont Colleges. The testing sites included the walkways between Parsons and Olin, the path near the unrustable statue, and between Jacobs and Keck. The equipment used included the 555 Timer circuit, the wearable casing prototype, and cameras for capturing participant gait and timing data.

Participants were instructed to walk naturally and safely along the designated path while being recorded. During the session, three distinct evaluations were conducted. The first involves the participant independently donning and removing the device to assess the intuitiveness of the attachment mechanism. The second evaluation measured the synchronization between the metronome clicks and the heel striking the ground during uninterrupted walking. In the final test, participants were to repeat the walking task while performing simple multitasking activities designed to simulate real-world distractions. This included solving mental math problems and engaging in casual conversation, which helped evaluate the user's subconscious attention to both their walking cadence and outside distraction.

All tests were video recorded for post-analysis. Timing data was extracted to measure the lag between metronome cues and foot strikes, providing a quantitative assessment of user synchronization. Participant feedback was collected at the end of each session to inform future design refinements. The data collected from the testing phase helps to identify user challenges and metronome efficacy, ultimately guiding improvements to the wearable device design and effectiveness for gait training for Parkinson's patients (See Appendix A for more). However, the team also acknowledges that prolonged use of the device might also improve the user's ability to multitask while following the cues.

3.2 MULTITASKING

The multitasking activities were selected to represent common, everyday scenarios that require divided attention while walking. Research has shown that this divided attention, caused by cognitive loads, can lead to impaired mobility [16]. Mental math problems provide a controlled cognitive load that engages working memory and processing. Conversational prompts simulate typical social interactions, requiring participants to split attention between verbal engagement and coordination with the metronome clicks. Therefore, these two multitasking abilities were chosen to evaluate whether or not mobility was impacted due to divided attention between auditory and other cues.

The questions prepared were:

1. Mental Math
    a. 5 x 24 (120)
    b. 7 x 8 (56)
    c. 17 x 3 (51)
    d. 12 x 9 (108)
    e. 30 x 7 (210)
    f. 4 x 19 (76)
    g. 20 x 15 (300)
    h. 13 x 8 (104)
    i. Count backwards from 57 in groups of three (57 54 51 …)
    j. Count backwards from 82 in groups of 12 (82 70 58 …)
2. Holding Conversations
    a. "How was your day today?"
    b. "Do you have anything exciting happening this week?"
    c. "Are classes going okay?"
    d. "Any plans for the Summer?"

Test users were asked to perform each set of tasks twice, once as a control (i.e. without the prototype) and another time as a comparison with the prototype, so the delay due to the task was measured. The results of the tests were compared and users were rated on how well they completed each task compared to the control, which was then analyzed to see how much the use of the device impacts movement, cognitive thinking, and motor function. The results of the individual's mental math tests shown below in figure 11 indicate no correlation between multitasking speed and the use of a metronome. Therefore, the results are inconclusive as to whether using a metronome will decreases the ability of users to solve mental math problems.

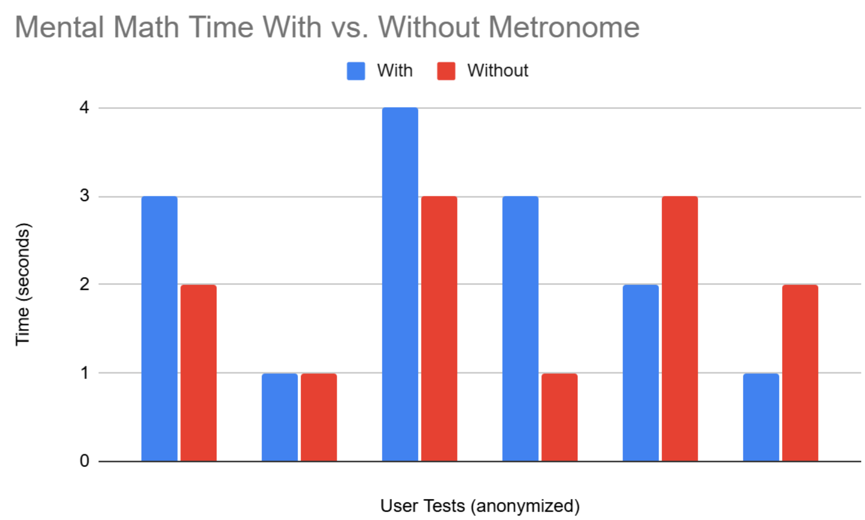

Figure 11. Change in user ability to solve mental math

Note: The data is anonymized for the test users' privacy.

3.3 TIME DELAY QUANTIFICATION

The second test method for the device aimed to quantify how well the users' gait matches the ticks of the metronome. This testing consisted of quantifying the delay between metronome clicks and feet making contact with the ground. To set up this experiment, a phone was fixed on the ground about 1 meter away from the user's walking path. Using the phone camera, a video was taken of the user walking, in which the metronome clicks are also heard. As expected due to the kinematics of gait, the user's foot first touches the ground at their heel. Therefore, based on close analysis of the video, the time at which users' heel first made contact with the ground was recorded. This was repeated for the entirety of their gait cycle for both their left and right feet. In addition to this, the times at which the metronome clicked, heard very clearly in the video, were also recorded.

In order to test whether the metronome clicks had an impact on dictating gait, the relationship between time of metronome click and time when feet hit the ground was evaluated. The results for one test user is shown in figure 12 below. As shown in the plot, the time between metronome clicks and feet hitting the ground exhibit a strong linear relationship. This strong linear relationship was also observed for all other test users. This result leads the team to conclude that metronome clicks have some influence, and that users are sticking well to the beat they hear.

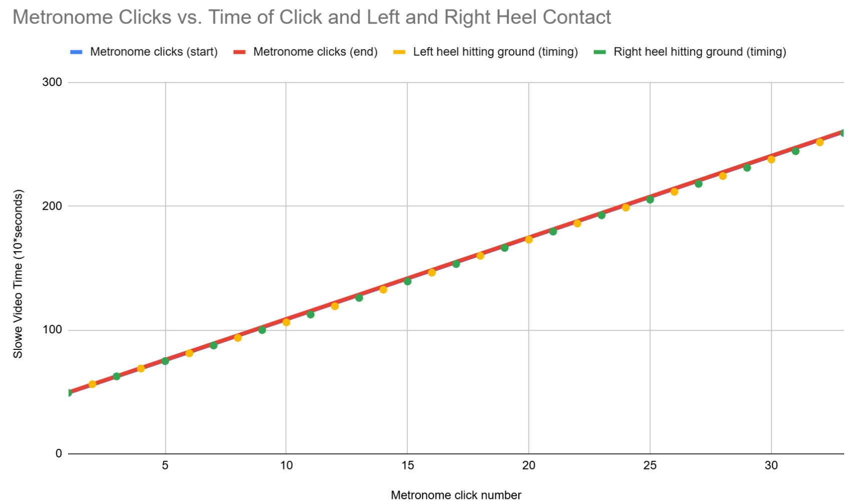

Fig 12. Plot of metronome click time vs. feet touching ground time

By finding the difference between the time when the metronome clicks and when the feet hit the ground, the time delay between the two events was quantified. For each user, the average time delay was computed, as well as the standard deviation of these delays. In order to analyze when the average time delay of all the users exhibited normal behavior, a box plot was created, which is shown in figure 13. The two plots represent the average differences for the left foot and right foot respectively. As shown by the box plot in the figure, the average differences are very similar and there is a tight grouping of the averages having a range of less than 0.2 seconds for both feet. This is further indication of the effectiveness of metronome clicks, or auditory cues, on users' gait.

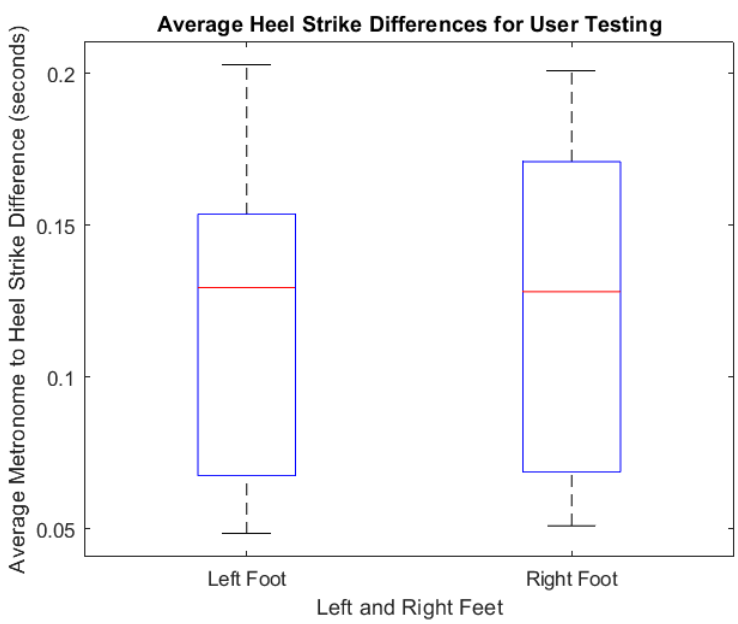

Fig 13. Plot of average time delay for all users tested

The standard deviation data was used to compare the control test to the test user's multitasking test. The data, reproduced in Table 1, showed that the deviation in all the users' gait cycle offset from the metronome was quite small and did not change much from the control test without distractions. This indicates that users were able to walk in time with the metronome, and also supports the hypothesis that a cueing metronome helps a user keep a steady gait cycle even when multitasking.

Table 1. Standard deviations of user gait cycle offset from a metronome

	Control Test SD	**Conversation Test SD**	**Mental Math Test SD**
User A	L: 0.0223 sec R: 0.0329 sec	L: 0.0452 sec R: 0.1749 sec	L: 0.0335 sec R: 0.0365 sec
User B	L: 0.0744 sec R: 0.0758 sec	L: 0.0713 sec R: 0.0766 sec	L: 0.0795 sec R: 0.0791 sec
User C	L: 0.0380 sec R: 0.0379 sec	L: 0.0603 sec R: 0.0733 sec	L: 0.0547 sec R: 0.0574 sec

One note with the standard deviation data is that for User A, their standard deviation for their right foot during the conversation test is much higher than the other deviations for both their left and right foot. Upon further analysis, it was found that during this test, they missed some beats when turning in the opposite direction. The test path required users to walk to a point and back, and the u-turn is where this error in data occurred. Aside from this data point, all other standard deviations are well within 0.1 seconds of each other (per user), so it was concluded that there is negligible variation in cadence when multitasking.

4. FUTURE RECOMMENDATIONS

In order to create a more robust design that effectively improves FoG, other cueing mechanisms can be implemented. In addition to auditory cueing, which was the team's primary focus, visual and haptic cueing could be added on to the design. Similar to the laser cane [9], a mechanism to shine a laser on the ground to act as a visual cue could be implemented onto the existing design. This can be implemented with the existing electronics and placed inside the housing, which can have a small hole through which the laser can shine. Instead of interfacing it with the current PCB, the laser could also be attached to the bottom of the mechanical housing, providing a constant beam that will act as a visual cue. Haptic cueing could also be implemented onto the existing design. In order to do this, the existing device would need to be integrated onto a cane. A vibrating sensor could be added onto the existing custom PCB and output vibrating pulses. These pulses would align with the timing of the metronome clicks, supplementing existing sensory cueing. A small mechanical system could be designed such that these sensations are felt in the user's hand as they grip the cane. A more robust cueing device to improve FoG can be built from our existing design by adding on more features that create a larger sensory input to PD patients.

Other engineering improvements could be made to the system focused on in this prototype, including volume control. The current design is set to play the metronome at a constant volume; however, depending on the environment, higher or lower volume levels could be useful for the user. This can be done using amplifiers like an LM380N-8 and a second potentiometer to control it. While this was a consideration for this prototype, it required upgrades to some devices in the system, including the speaker, that were out of focus for the scope of the project.

The accuracy and consistency of user testing could also be improved. In analyzing the videos of the user walking, it was difficult to identify the precise moment the user's heel touched the ground. Therefore, the team suggests having the users walk barefoot for future testing. In order to identify the moment the heel touched the ground and record time values precisely, the team had to slow down the video. In order to do this more robustly, the team recommends using other video editing softwares. Additionally, the team acknowledges that the mental math questions, which were asked to the users with and without the metronome, varied in difficulty. Therefore, the team recommends standardizing these questions to ensure that the metronome's effects are analyzed independently. In the current testing plan, the user was instructed to walk to follow the beat of the metronome. Since the metronome speed was set to the user's natural gait speed, the user could have subconsciously ignored the metronome and walked according to their normal gait speed. Therefore, in order to truly test how effectively users were able to keep pace with the metronome, the team recommends changing the rate of metronome beats. Using non-consistent beats would have allowed the team to test the user's actual response to the metronome.

APPENDIX A.

Purpose:
We are developing a wearable attachment containing a 555 Timer (metronome) circuit for gait synchronization. We want to evaluate how effectively users match their walking pace to the metronome, their ability to multitask during use, and the ease-of-use for various scenarios (wearing on the body or attaching to a walking aid).

Although the testing we will be doing isn't done on Parkinson's patients, this will allow us to create base case data to use. Past that, this could develop into predictive simulation for freezing of gait in Parkinson's patients.

Participant Criteria:
We are looking for healthy non-Parkinson's participants. For this initial testing round we want about 3 to 5 participants.

Testing Environment:
The location for the testing will be a controlled outdoor path on the Claremont College campus. It will be a section of flat ground that's approximately 15 feet.

The possible locations are the walkway between Parsons and Olin, the walkway from Platt past the unrustable statue, and the walkway from Jacobs to Keck.

Equipment:
- 555 Timer circuit
- Wearable circuit casing
- Cameras

Multitasking Activities:
- Mental Math
    - 5 x 24 (120)
    - 7 x 8 (56)
    - 17 x 3 (51)
    - 12 x 9 (108)
    - 30 x 7 (210)
    - 4 x 19 (76)
    - 20 x 15 (300)
    - 13 x 8 (104)
    - Count backwards from 57 in groups of three (57 54 51 …)
    - Count backwards from 82 in groups of 12 (82 70 58 …)

- Holding Conversations
    - “How was your day today?”
    - “Do you have anything exciting happening this week?”
    - “Are classes going okay?”
    - “Any plans for the Summer?”

Instructions for Participant:
“Please walk naturally and safely, and if at any point you feel uncomfortable please let us know and we will pause or stop the testing.

We will be recording your walking with video and collecting timing data to precisely measure your steps. Your identity will remain confidential and all recordings will be used for this research alone.

Alright, thank you for your participation today, let me tell you a little about our project today. Our team has been developing a wearable metronome designed to help in the training of Parkinson's patients to decrease Freezing of Gait (FoG). Today we will just be looking at how easy the product is to use and how it affects your walking. Your feedback and the data we collect will help improve the design.

We will be performing three tests. The first test is having you put on and take off the device by yourself to attach to your body or a walker. Secondly, we will test walking at various speeds to the sound of the metronome. We will be capturing your walking via a camera. Lastly, we’ll have you do the same thing again but add in some activities like short conversations or performing mental tasks (like times tables) or playing a video game.

We will talk about your overall experience at the end of the testing. If you’d like to stop your participation at any point, just let us know. Any questions? [wait for response, and after any questions are answered:] Do you consent to contributing your responses and videos of your walking for the purposes of this class project? Would it be okay if we share your video with our class and final report, which may be public?” (They don’t need to answer yes to this question to participate, but you do need a yes if you plan to show these videos/images from the videos.)

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