A Novel Wearable for Active Prevention of Falls Through GRU-Based Gyroscopic Inference and Center of Mass Manipulation

INTRODUCTION

What is Freezing of Gait (FOG)?

- An episodic gait pattern characterized by the **patient's inability to step**.
- It occurs when initiating or turning during walking, and it is exaggerated with perception of tight surroundings.

Why Freezing of Gait (FOG)?

- It is one of the most disabling symptom of Parkinson's Disease (PD) which impairs balance, increases falls, and reduces quality of life.
- It has a prevalence of **35.8% in PD patients, or around 3.043 M patients across the world**; however, it is one of the most poorly understood symptoms.[1][2]

Human Balance Systems

Humans are able to balance by maintaining the body's center of mass above their base of support.

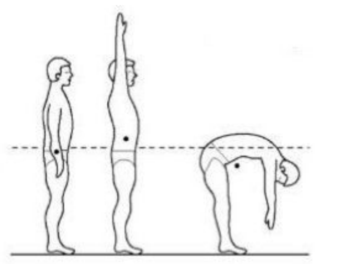


Figure 1. Human center of mass in relation to the base of support in various positions.

CURRENT SOLUTIONS AND DRAWBACKS

Current solutions suffer from weakening muscles, rendering rehabilitation ineffective.

- Use of mobility aids, such as wheelchairs and canes can provide insufficient exercise to certain muscles which leads to a variety of issues.

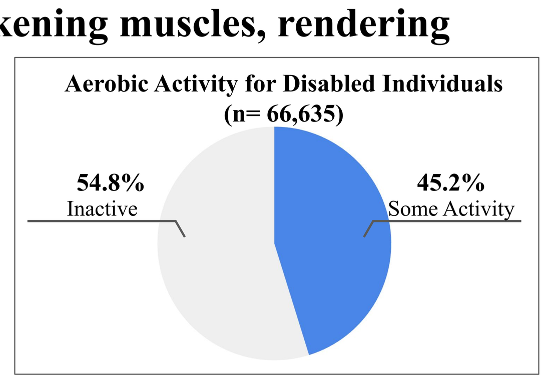


Figure 2. 54.8% of disabled individuals receive no aerobic activity with use of mobility aids.

- Impediment of neurogenesis
- Weakened brain-muscle activations
- Osteoporosis
- Cardiovascular disease

These issues actively worsen the patient's situation, especially for long-term rehabilitation after treatment.

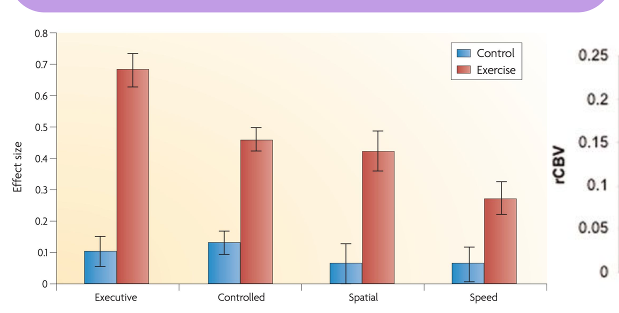


Figure 3. Exercise has a large weight on the cognitive ability in various tasks and inactivity could have a vast effect on patients.

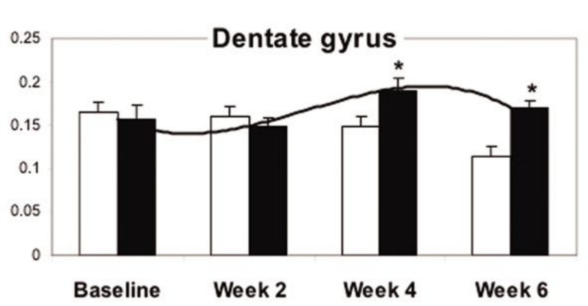


Figure 4. Cerebral blood volume, correlated with neurogenesis, increases with aerobic activity (filled) and decreases with inactivity (empty).

- Such various effects can have great adverse effects on PD patients as it can further lower their cognitive ability by weakening neural connections through lack of neurogenesis.

Key Problem: Widely-used mobility aids accompany drawbacks that make them ineffective as a **long term solution to falls and FOG**. For wheelchairs, it is lack of exercise, and for walkers/canes, it is osteoporosis.

MY APPROACH

1. **Construct a device that uses weighted pendulums to maintain the user's balance in accordance with the center of mass (COM) kinematic model.**

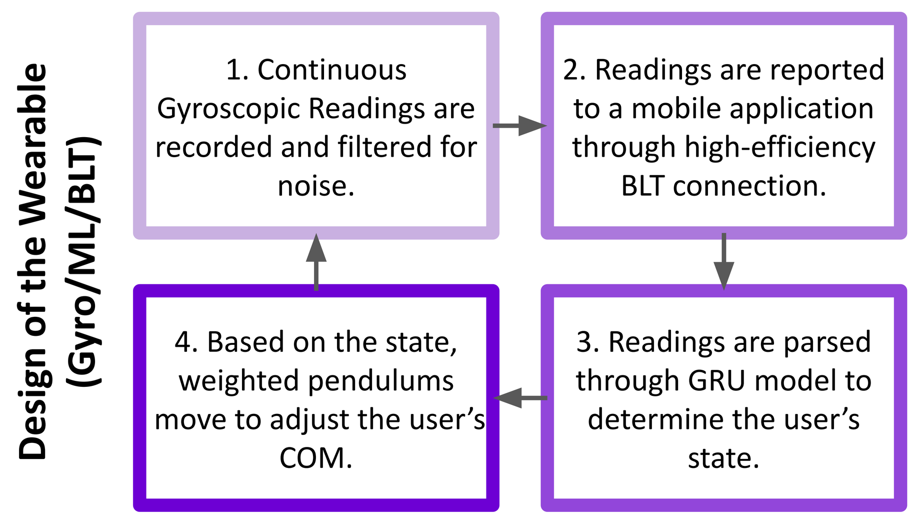
$$x_{cm} = \left(\sum_{i=1}^{N} m_i x_i\right) \Big/ \sum_{i=1}^{N} m_i$$

2. **Design various frameworks to optimize for equal weight distribution.**
3. **Utilize a deep GRU-Model to infer the state of the user.**
4. **Employ Kalman filtration to improve accuracy by eliminating noise.**
5. **Develop a bluetooth-based mobile application for accessible interface.**

DESIGN CRITERIA

- **The device should distribute load in order to not exert greater than 25 Newtons of force in any given location.**
- **The gyroscope should have a bias instability less than 2 degrees / hour.**
- **The deep learning model should have an F1-Score greater than 0.90.**
- **The success rate of maintaining balance should be greater than 80%.**
- **The device should have a latency between angle detection and action of less than 2 seconds.**
- **The battery life should be greater than 15 minutes of continuous use.**

ARCHITECTURE AND LOAD DISTRIBUTION



MATERIALS LESS THAN 5KG AND DISTRIBUTED WITH < 25N PER POINT!

The rearranged COM equation:

$$b\cos(90-a) = \frac{bc\cos(d)}{2f+c} + \frac{2f(-g+(b-h)\cos(d))}{2f+c}$$

a = max. natural inclination
b = dist. ground to waist
c = body weight d = max. device inclination device
f = pendulum shaft length g = pendulum shaft length
h = pendulum to waist length

- According to the use of the equations with average statistics of elderlies above 65, the pendulums have to be 1.8 kg each.
- The pendulum shafts would also be 50 cm in length.

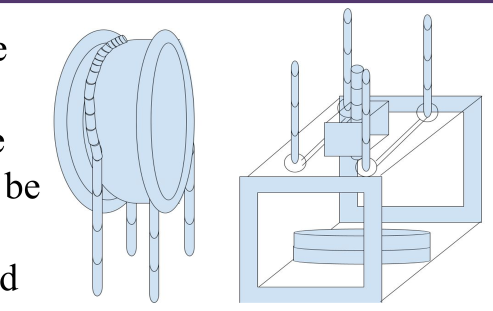


Figure 5. Initial schematic of the weights.

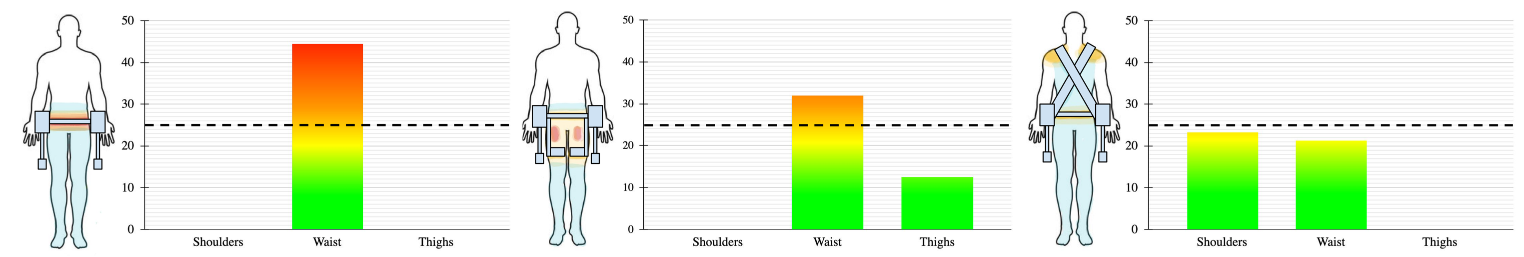
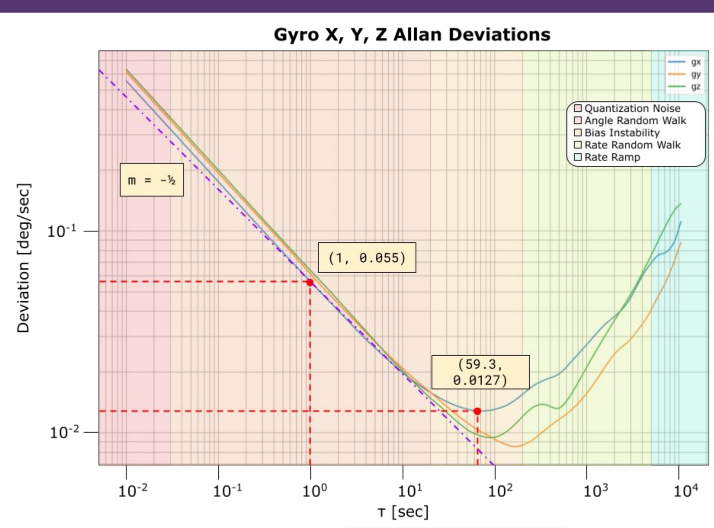


Figure 6. Three major iterations of the prototype and their corresponding weight distribution recorded by a force-gauge. Load maps represent qualitative data of the location and magnitude of stresses as reported by the user after 45 minute use.

CIRCUITRY AND MITIGATING GYROSCOPIC ERROR ACCUMALATION



Angular Random Walk: 3.30 deg/√hr
Bias Instability: 68.91 deg/hr

- Allan Deviation analysis was used to identify variance in bias over time for the stationary MPU6050
- Slope of -½ reveals **White Gaussian Noise**
- Data was collected for over 6 hours at 100 Hz, delivering **> 2.5M data points**.
- **Kalman Filtration** would be most effective in eliminating gyroscopic bias

Figure 7. An Allan Deviation plot of the MPU6050 was constructed in order to determine the quality and magnitude of the noise.

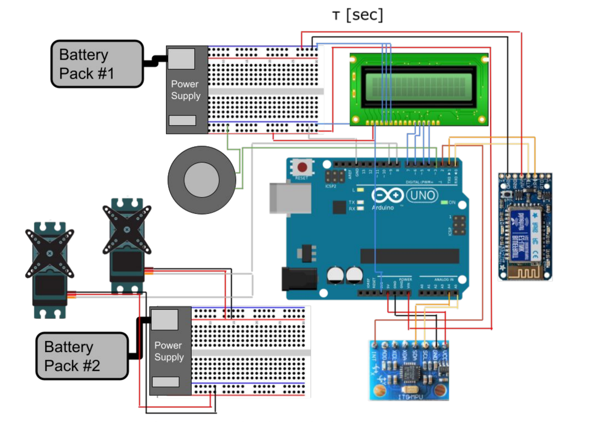
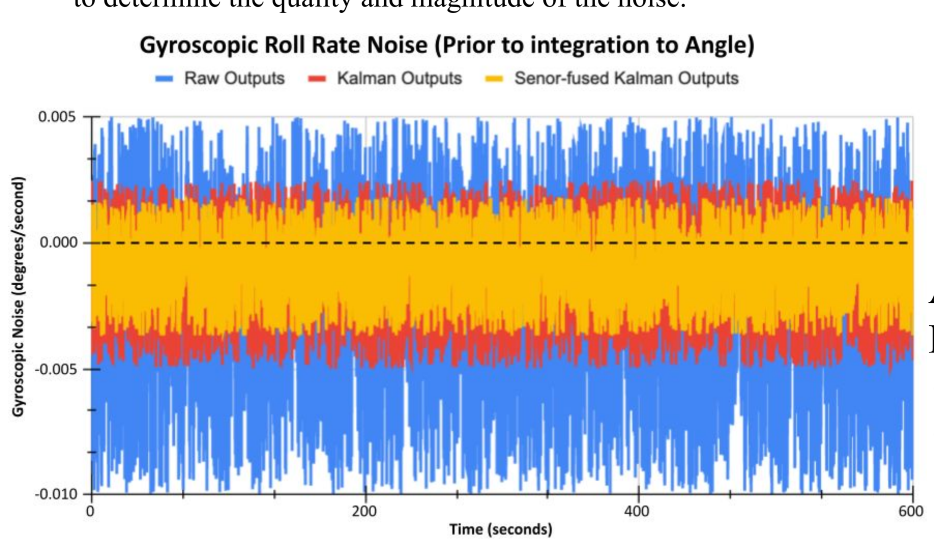
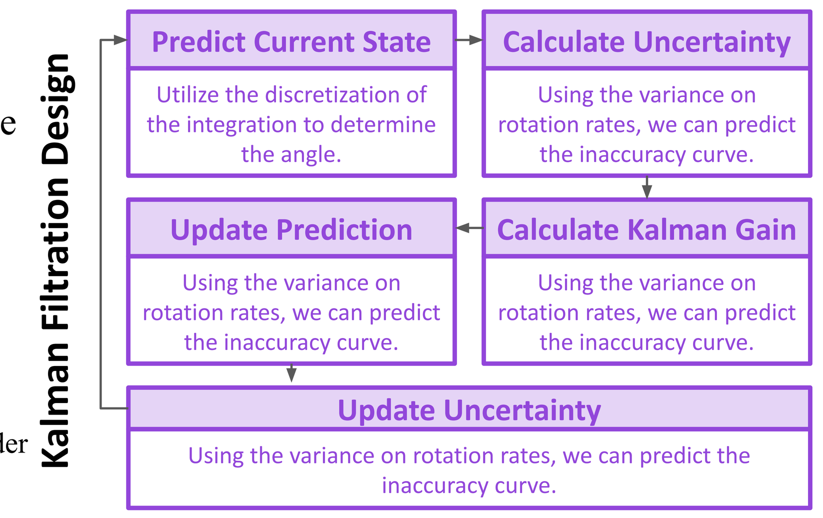


Figure 8. A pinout of all of the devices. NOTES: Motor uses a scaling formula derived from the COM formula to exert minimal force on the user. The MPU6050 uses I²C Protocols.





The integration and its discretization to determine angle from angular velocity:

$$Angle_{kalman} = \int_{o}^{k*Ts} Rate_{kalman} \times dt$$

$$Angle_{kalman}(k) = Angle_{kalman}(k-1) + Rate(k) \times T_s$$

k = iteration number T_s = iteration length $Rate_{kalman}$ = raw angular velocity

Angular Random Walk: 0.096 deg/√hr
Bias Instability: 0.58 deg/hr

- 93.3% LESS BIAS INSTABILITY
- Sensor fusion was utilized by using trigonometric functions to isolate angles then used for updating the measurement curve.

GRU-MODEL FOR PREDICTION

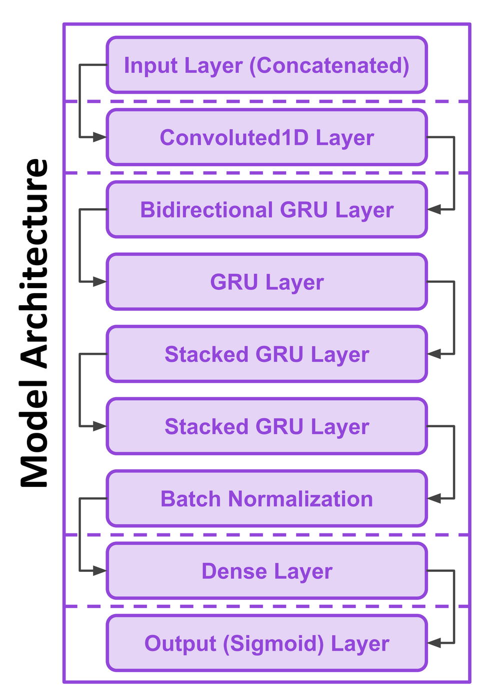
Initial data was collected by positioning myself in three states:

- Unbalanced, standing, walking, falling abruptly.
- Characteristics from FOG were utilized for the unbalanced label.

Model Quantization

- To reduce memory usage, quantization classifies angular data into discrete intervals.

Low resolution categorization in intermediate angles and **dense categorization** in upright angles increases efficiency.



Speciality of GRU Units

- Update Gate and Reset Gate can control the flow of information into a network
- Mitigates vanishing gradient issue with RNNs

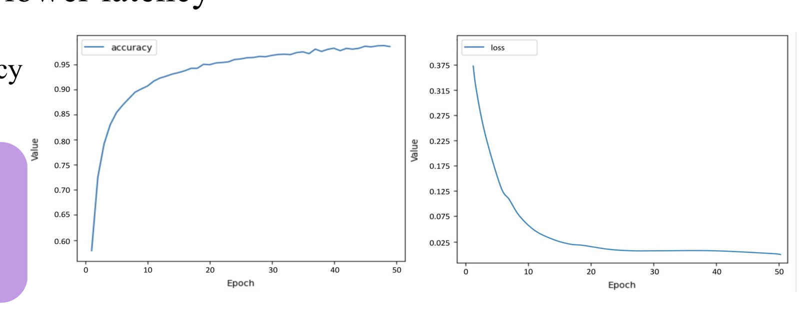
GRU Units were used to deal with computational restrictions on smartphones.

- Fewer parameters and computations
- Faster runtimes and outputs with lower latency

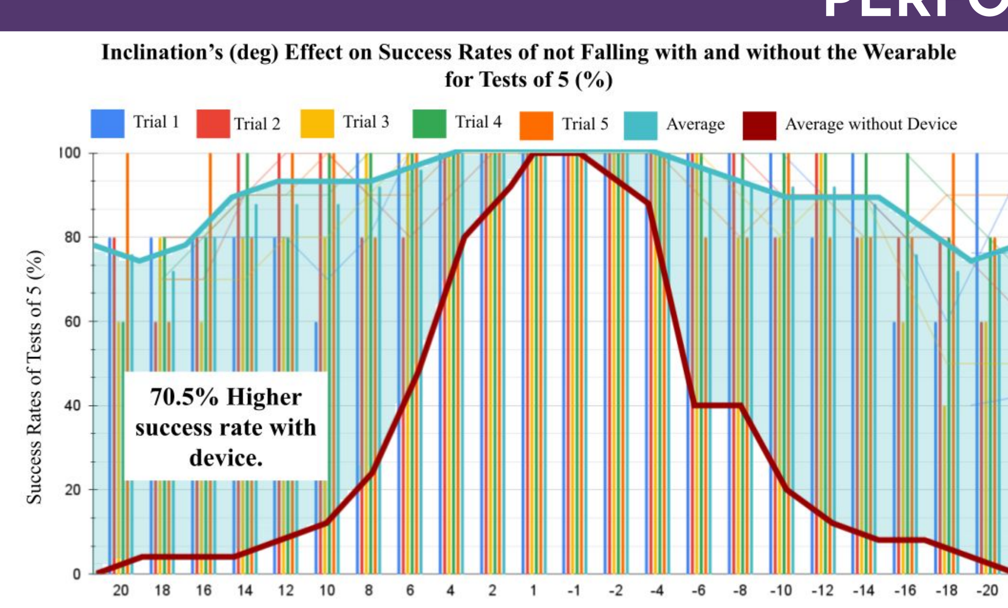
True Class	Predicted Class: Unbalanced	Predicted Class: Other
Unbalanced	True Positive 97.44%	False Positive 2.56%
Other	False Negative 5.28%	True Negative 94.72%

Figure 9. The GRU model achieved an accuracy of .9608 and a TP-rate of 0.9744.

MODEL ACHIEVED F1 SCORE OF .9369!



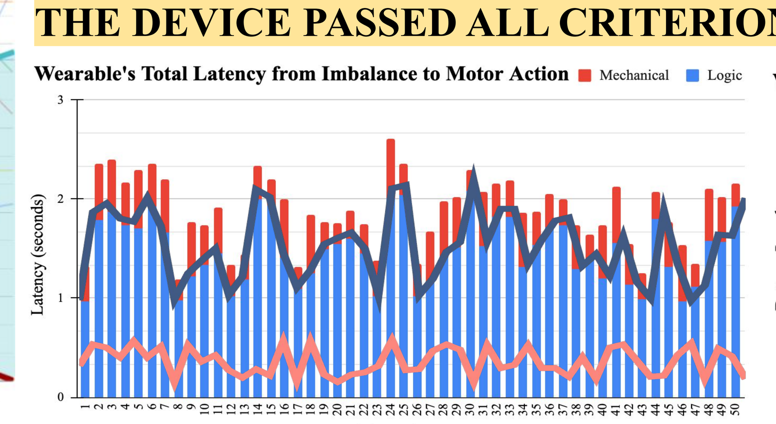
PERFORMANCE VALIDATION

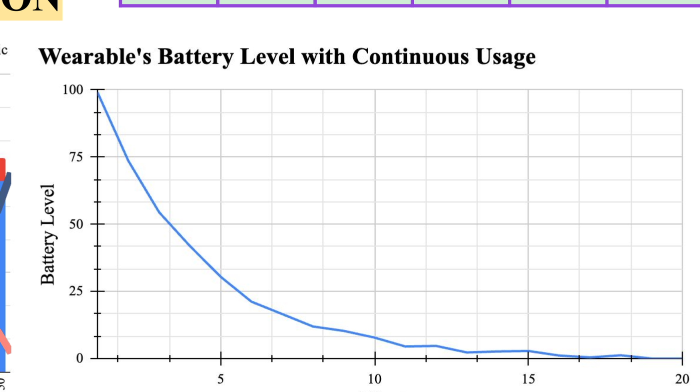


The device had a success rate **70.5%** higher than without the device, an average latency of **1.88s**, and a battery life of **18min** continuous use.

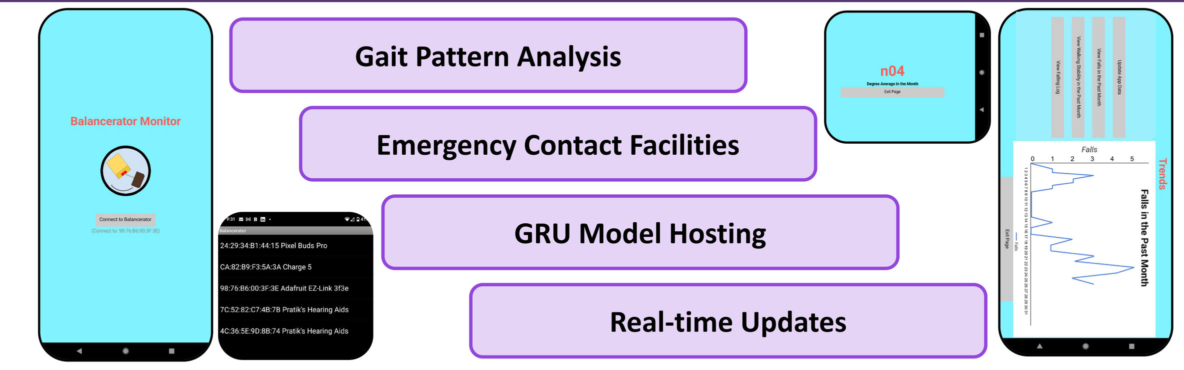
#1	#2	#3	#4	#5	#6
23.3 N	0.58 BI	.9369 F1	85.25 %	1.88 sec	18 min

THE DEVICE PASSED ALL CRITERION





MOBILE APPLICATION



SETBACKS AND LIMITATIONS

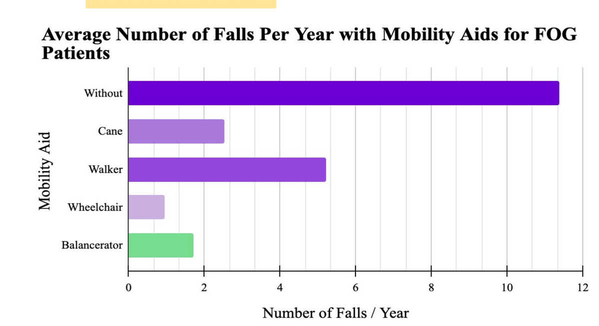
- Constructing the motor-shaft connection
- Establishing I²C connection with the gyroscope
- Managing layer shapes in the model
- Creating "request" actions and synchronizing Arduino timings to the application

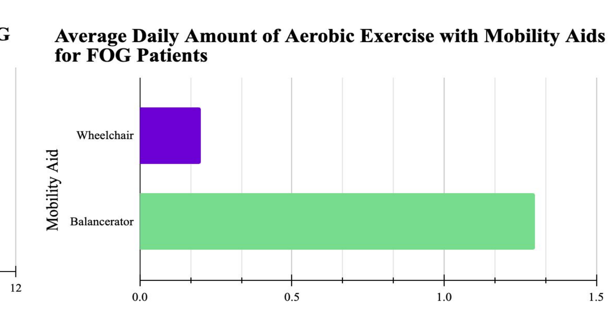
- The device was tested with me as the test subject- further tests could include people who actually experience FOG
- Latency and model performance was tested on only the Google Pixel 7 Pro
- Gyroscopic readings for tests may have been altered by power fluctuations

CONCLUSIONS

Prototype reduces falls without negative side-effects.

- Improved falling rate from canes and walkers, without limiting aerobic activity and creating negative impacts
  - Weight distribution achieved by the prototype ensures no side-effects to specific areas
- Expected number of falls is 1.5x of canes and exercise is 4x wheelchairs[3]





Provides a tool for the improvement of millions of lives.

- Bluetooth connectivity makes disease progression trackable by doctors
- Emergency contact features reduce time for help
- Inexpensive microchips and design makes the product more accessible
  - Average wheelchair is > $100; device is ≈ $40 at mass sale

Daily Mental Impact on Patients

- Boosts confidence and independence for patients to complete their daily activities and chores on their own accord
- Provides a significant increase in quality of life for the patient

Further improvements.

- Vestlike design to make the model easy to wear and less clumsy
- Field Programmable Gate Array and offline learning for optimization

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[1] Ge, Hongliang, et al. "The Prevalence of Freezing of Gait in Parkinson's Disease and in Patients With Different Disease Durations and Severities." Chinese Neurosurgical Journal, vol. 6, no. 1, BioMed Central, May 2020, https://doi.org/10.1186/s41016-020-00197-y.

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[3] Abou, Libak, and Laura A. Rice. "Frequency and Characteristics of Falls, Fall-related Injuries, and Fear of Falling Among Wheelchair Users With Spinal Cord Injury." Journal of Spinal Cord Medicine, vol. 46, no. 4, Maney Publishing, Aug. 2022, pp. 560–68. https://doi.org/10.1080/10790268.2022.2097995.

Images:

[1] 12gMz.jpg (284×211). i.stack.imgur.com/12gMz.jpg.

[2] Hollis, NaTasha D., et al. "Physical Activity Types Among US Adults With Mobility Disability, Behavioral Risk Factor Surveillance System, 2017." Disability and Health Journal, vol. 13, no. 3, Elsevier BV, July 2020, p. 100888. https://doi.org/10.1016/j.dhjo.2020.100888.

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All other images created by researcher (Krishna Bhatt).