ReBoot: A SMART SHOE SYSTEM FOR IN-HOME PARKINSON'S MOTOR ASSESSMENTS

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***Abstract*— Parkinson's Disease (PD) is a progressive neurodegenerative disorder characterized by both motor and non-motor symptoms, requiring frequent, objective monitoring to optimize clinical management. Traditional in-clinic assessments are limited by infrequent evaluations and subjective ratings. To address this, we present ReBoot, a wearable system designed for in-home, quantitative assessment of lower-limb motor symptoms in persons with PD (PwPD). The ReBoot system integrates force sensors and inertial measurement units (IMUs) into a commercial outsole, interfaced with a user-friendly Raspberry Pi tablet application for guided task execution and data collection. We validated ReBoot's sensor accuracy against a gold-standard XSens IMU system in ten healthy participants across standard motor tasks (toe tapping and leg agility), showing agreement in key features such as peak amplitude and inter-peak intervals. Subsequently, we conducted a 10-day feasibility study with three PwPD, assessing task performance in ON and OFF medication states within home environments. Analysis revealed that ReBoot could reliably capture medication-related motor fluctuations, with leg agility metrics showing greater sensitivity to dopaminergic states compared to toe tapping. Our results support the feasibility of ReBoot as a low-cost, scalable alternative to lab-based assessments for continuous motor monitoring in PD. These findings highlight ReBoot's potential to complement existing clinical evaluations, inform personalized treatment strategies, and enable remote symptom tracking, thereby contributing to more responsive and data-driven PD care.**

Keywords—Parkinson's Disease, toe-tapping, leg-agility, Wearable Sensors, In-home Monitoring, Motor Assessment.

I. INTRODUCTION

Parkinson's disease (PD) is a progressive neurodegenerative disorder that affects millions of people worldwide. Over 1 million people are currently diagnosed with PD in the United States, with a projected growth of 60% (1.6 million) by 2037 its total annual economic burden is projected to surpass $79 billion [1] PD is characterized by both motor and non-motor symptoms. The four cardinal motor symptoms include akinesia (decreased initiation of movement), bradykinesia (slowness of movement), rigidity, and resting tremors[2]. Other symptoms encompass cognitive impairment, sleep disorders, depression, and postural instability. These symptoms result from the death of dopamine-producing cells in the Substantia Nigra pars compacta (SNpc), a region of the brain that is essential for motor control [2]. Interventions to manage symptoms range from medications like Levodopa, specialized physical therapy programs and deep brain stimulation [2]. The progressive aspect of PD requires routine and objective monitoring of symptoms to track disease progression, evaluate treatment efficacy, and adjust therapeutic interventions accordingly [3].

The current gold standard for clinical assessment is the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) [4]. This scale consists of four parts that evaluate various aspects of PD symptomatology, including motor and non-motor experiences in daily living conditions. Part III of MDS-UPDRS involves visual assessment of a PwPD performing certain movement tasks by a trained rater. While comprehensive, the reliance on in-clinic MDS-UPDRS assessments, typically conducted every 3-6 months, presents practical challenges in temporal resolution and interrater variability [5]. Additionally, the brief nature of the clinical visits may not provide a complete picture of the patient's conditions, as symptoms can fluctuate throughout the day depending on medication intake [4].

To address this, various technological solutions for objective motor symptom tracking have been explored. Computer vision-based systems have been utilized to analyse motor features from video recordings offering non-contact assessment of PD symptoms; however, they require a line of sight [6]. Concurrently, wearable sensor technology has gained significant traction, employing inertial measurement units (IMUs), pressure sensors, and other modalities embedded in items like wristbands, insoles, or garments to quantify movement patterns, gait parameters, and tremor characteristics [7][8]. While these approaches offer valuable objective data, challenges related to system usability, data interpretation, comfort for long-term wear, and the need for in-lab setups or complex data processing persist for many existing solutions [9].

In response to these challenges, we propose the ReBoot system, a wearable shoe sensing system designed specifically for the assessment of lower body motor symptoms in PD within home environments (see Fig 1). The ReBoot system is part of a broader PD monitoring solution that includes the previously developed iTex gloves for upper body assessment of PD [10]. This paper presents the following contributions:

- The design and development of the ReBoot system, an instrumented wearable outsole, and a user-friendly tablet interface for guided, in-home assessment of lower-limb PD motor symptoms

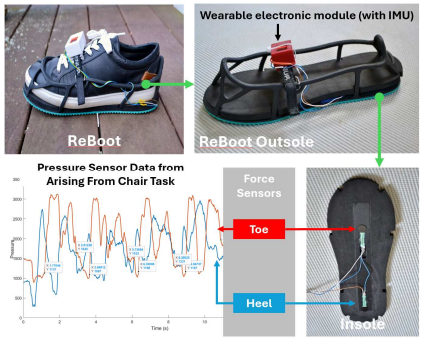


Figure 1: Overview of the ReBoot System.

- Validation of the ReBoot system's sensor data accuracy against a gold-standard inertial motion capture system (XSens) in a cohort of healthy participants
- A feasibility study demonstrating the ReBoot system's utility for in-home monitoring of PwPD motor symptoms, highlighting its capability to capture quantitative differences in motor performance between 'ON' and 'OFF' medication states.

II. Materials & Methods

A. ReBoot: Smart Shoe Development

The ReBoot system enables in-home quantitative assessment of lower-limb motor symptoms in PwPD, comprising wearable Smart Shoes and a raspberry pi tablet. The Smart Shoe (Fig. 1) was developed by instrumenting a commercial EvenUp® outsole, selected for its stability and attachability to users' footwear. Each shoe integrates two Alpha® membrane force sensors [11] with an active area of 14.7 mm^2 at the heel and metatarsals for plantar pressure, and an M5StickC Plus ('M5' henceforth) unit[11]. This unit, encased in a 3D-printed TPU housing on the foot's dorsum, contains an ESP32 microprocessor (BLE capable) and a 6-axis IMU (3-axis accelerometer, 3-axis gyroscope). A custom PCB with resistor divider circuits interfaces the pressure sensors to the M5's Analog to Digital converter. The M5 samples sensor data at an average of 57 Hz, empirically chosen to balance data quality, wireless reliability, and power, transmitting comma-separated character lines via Bluetooth. The sampling rate was chosen based on past research assessing the impact of sampling rate on lower limb kinematics [12].

B. Tablet Computer Application Development

The tablet application system uses a Raspberry Pi 4 with a 7-inch touchscreen as the user interface and data hub (Fig. 2). Developed in Python with Flask, it provides visual/auditory prompts for MDS-UPDRS Part III-derived motor tasks. The interface provides clear, step-by-step instructions for each task, including both visual cues and audio prompts to ensure users can easily understand and follow the assessment protocol. It receives data from both shoes via Bluetooth SPP. Receiver Python micro-services parse incoming payloads, which are then transferred locally to the main Flask application via MQTT (Paho MQTT broker) for robust, non-blocking data stream management to the application. Data is cached locally and then uploaded to a secure Google Drive via RClone. Post-session, the app administers

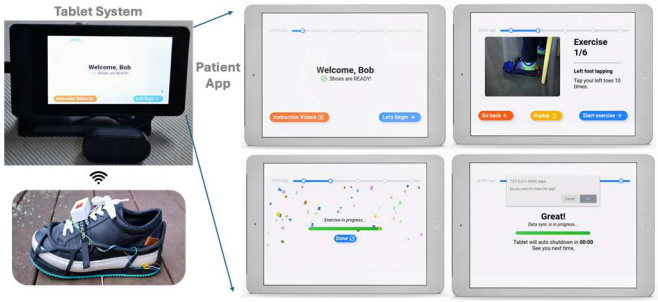
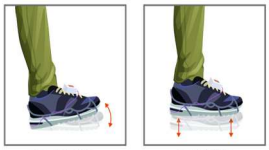


Figure 2: The ReBoot System (left) and patient app with movement task instruction screenshots (right).

questionnaires on medication timing, tremor, dyskinesia, and sleep quality. Error handling and auto-reconnect features were implemented for unsupervised home use. Additionally, the system includes remote monitoring capabilities, allowing researchers to track system performance and user adherence without requiring direct interaction after deployment.

C. Protocol and Study Participants

This study was approved by the University of Rhode Island Institutional Review Board (IRB #1883825-5), with informed consent obtained from all participants. Two participant groups were recruited. For validation of the Reboot system against the



Task	Instruction
Toe Tapping	With the heel on the ground, tap the toes 10 times as big and as fast as possible. (Each side independently)
Leg Agility	Raise and stomp the foot on the ground 10 times as high and as fast as possible. (Each side independently)

Figure 3: Description of the lower limb movement tasks performed by participants

reference system, ten healthy adults (n=10, 7M/3F, 26.2 ± 4.61 yrs) without neurological/musculoskeletal conditions participated. Healthy participants wore ReBoot shoes and XSens MVN Link IMU suit (7 lower-body sensors, 240 Hz). ReBoot data was collected concurrently to evaluate if the measurements were similar to the reference XSens IMU system. The Feasibility Study was conducted in PwPDs' homes for 10 days, three males with PD (72 ± 7.21 yrs, MoCA > 19, stable medication) were recruited. After in-person setup/training, PwPD performed tasks twice daily: pre-medication (OFF state) and 0.5-6 hours post-medication (ON state), maintaining usual medication schedule. Daily motor data and questionnaire responses were collected, followed by an exit usability survey. All participants performed two MDS-UPDRS derived Motor Assessment Tasks, Toe Tapping (10 reps/foot, max amplitude/speed, heel down) and Leg Agility (10 reps/foot, max height/speed foot stomp; Figure 3).

D. Data Processing and Analysis

Raw sensor data from ReBoot (IMU, pressure) and XSens (IMU) were processed to extract biomechanical metrics about the movements. Signal Preprocessing for the validation study involved up-sampling ReBoot IMU data from 57 Hz to 64 Hz (linear interpolation) for time-synchronized comparison with XSens data (240 Hz, subsequently down-sampled to 64 Hz). For the feasibility study, ReBoot data was analyzed at its native

rate. Pressure sensor data from both studies were processed using an adaptive thresholding method on the summed pressure signal to detect heel-strike and toe-off events, enabling segmentation of gait cycles and task transitions.

Feature Extraction was performed for each motor task. For Toe Tapping (validation and feasibility), y-axis gyroscope data (sagittal foot rotation) was squared, normalized (0-1), and processed with a peak detector to extract peak angular velocity and inter-tap intervals. For Leg Agility, z-axis accelerometer data (vertical foot acceleration) underwent similar processing (squaring, normalization, peak detection) to extract peak acceleration and inter-stomp intervals. Equivalent kinematic features were extracted from XSens data using MVN Analyze software for validation. For the feasibility study, these ReBoot features were calculated separately for ON and OFF medication states. Statistical Analysis involved the use of paired t-tests (for discrete features) to assess IMU data from the M5 (for the ReBoot vs. XSens agreement. For the feasibility study, Welch's Two-Sample t-test compared ON vs. OFF state features for each PwPD. Significance was set at $p < 0.05$.

III. Results and Discussion

In this section, we describe the results of our validation study with healthy individuals and the feasibility with PwPD individuals. As part of the validation study, we intended to compare how our developed system performs compared to the gold standard XSens system. As part of the feasibility study, we intended to understand whether the features computed using our system could be used to assess the differences in PD symptoms during the 'ON' and the 'OFF' states of medication, and if so which feature and task would be most effective in characterizing the effect of medication.

A. Difference between features computed using Xsens and M5 of Healthy individuals for Toe-tapping activity

Given that Peak Amplitude and the Distance between peaks are important features for assessing the Toe tapping activity, we first wanted to validate these features computed from data collected using the IMU on M5 (Peak Amplitude_M5 and Distance between Peaks_M5) against that collected using the XSens (Peak Amplitude_XSens and Distance between Peaks_XSens) as gold standard. Figure 4 shows the boxplots of these features. We see that the boxplots for the features computed using both systems appear to be similar. Additionally, we found no statistically significant difference ($p<0.05$) between Peak Amplitude_XSens and Peak Amplitude_M5, and Distance between Peaks_M5 and Distance between Peaks_XSens. This suggests that our M5 system is capable of capturing the Peak Amplitude and Distance between Peaks for the Toe-tapping activity with reasonable accuracy.

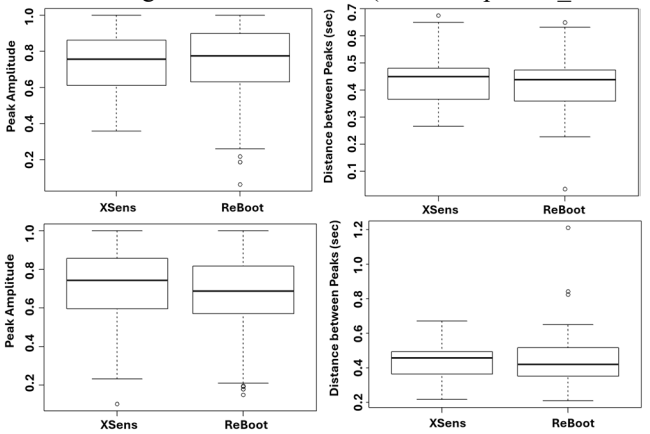


Figure 4. Healthy Participants - Leg Agility – Box Plots. Left shoe on the top and right shoe on the bottom. Peak amplitudes on the left and distance between peaks on the right. Note: M5: ReBoot system

B. Difference between features computed using Xsens and M5 of Healthy individuals for Leg-agility activity.

Having seen that the M5 was able to accurately capture Peak Amplitude and Distance between Peaks for the Toe-tapping activity, we wanted to perform a similar validation for the Leg-agility activity that involves greater leg movement compared to the Toe-tapping activity. For this, we performed a comparative analysis of the Peak Amplitude_M5 and the Peak Amplitude_XSens and the Distance between Peaks_M5 and Distance between Peaks_XSens (Figure 5). We found that similar to the Toe-tapping activity, there was no statistically significant difference ($p<0.05$) between the features. This suggests that the M5 was able to accurately capture the features (despite having greater leg movement) for the Leg-agility activity. This supports the use of ReBoot as a viable economical alternative to the XSens for characterizing the Toe-tapping and Leg-agility activity.

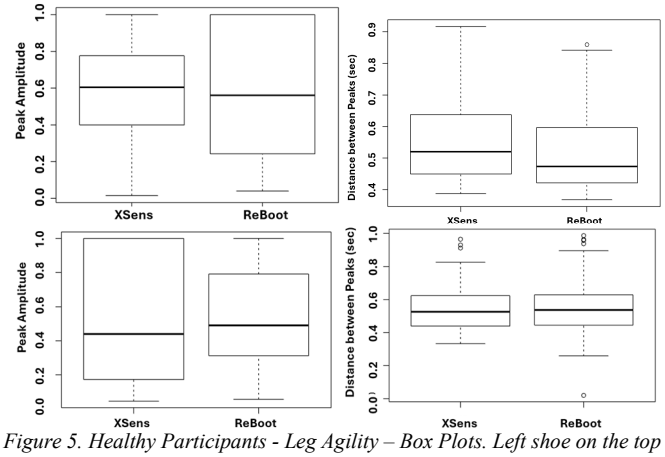


Figure 5. Healthy Participants - Leg Agility – Box Plots. Left shoe on the top and right shoe on the bottom. Peak amplitudes on the left and distance between peaks on the right. Note: M5: ReBoot system

C. Difference between features during the ON state and OFF state of PwPD individuals for the Toe-tapping Activity

Given that the ReBoot system was able to accurately capture the distance between peaks and peak amplitude for the Toe-tapping activity, we wanted to understand whether these features computed during the Toe-tapping activity could capture the effect of medication of PwPD individuals. For this we computed the mean distance between peaks and mean peak amplitude for 3 participants (PD1, PD2 and PD3) for both the legs (Figure 6). The Intra-group analysis showed that there was no significant difference between the Peak Amplitude ($p>0.05$) during the ON state and the OFF state for any of the PwPD participants. However, on comparing the Distance between

Peaks, for PD2 statistically significant difference ($p<0.05$) was obtained between the ON state and OFF state for both the right and left shoe, and a similar result was seen in PD3 for the left shoe. Such an observation possibly suggests that for the Toe-tapping activity, medication might have a significant impact on the frequency of taps rather than the amplitude for most individuals.

D. *Difference between features during the ON state and OFF state of PwPD individuals for Leg-Agility Activity*

Having seen that medication may impact the toe tapping frequency, we wanted to see its impact on the leg agility task. Similar to that for the Toe-tapping task, we have analyzed the features for the Leg Agility task. The Figure 7 shows the average Peak Amplitude and the Distance between Peaks before and after medication. Within-group analysis showed that the medication had a significant effect ($p<0.05$) on the task

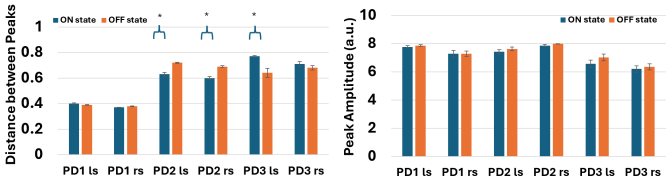


Figure 6. Distance between peaks and peak amplitude between the ON state and OFF state of PwPD individuals for Toe-tapping Activity

Note: * implies p <0.05, ls: left shoe, rs: right shoe

performance for the Leg-agility task. Specifically, unlike that in the case of toe tapping task, it appears that the medication has a significant effect for most PwPD individuals both in terms of amplitude except on PD1's right shoe and PD2's left shoe on the Distance between Peaks and Peak Amplitude, respectively. Thus, the leg agility task requiring a larger movement may guide characterization of the impact of medication more effectively compared to toe tapping. Though these preliminary results are promising, further exploration is warranted for generalizing.

IV. Conclusion

In this work, we have introduced ReBoot, an IMU and pressure sensor based platform for digitizing the assessment of the lower-limb motor exams in UPDRS. We have validated ReBoot against the widely accepted XSens gold standard for its accuracy in computing the Peak Amplitude and Distance between Peaks features with ten healthy participants. The results of our validation study are promising in setting ReBoot as a viable cost-effective to XSens for computing the Peak amplitude and Distance between Peaks features. Furthermore, we have also conducted a preliminary study with PwPD to assess the potential of ReBoot to characterize the impact of medication on the task performance in the standard tasks. The findings of our preliminary investigation suggest that there might be a difference in the efficacy of tasks that are capable of characterizing the impact of medication. Although the results of our study are promising, there exist certain limitations. One of the limitations is the sample size of the study with PwPD. It would be imperative to extend this study to a larger population before generalizing the results. Additionally, it would be important to extend more tasks for such an investigation. Notwithstanding the limitations, the impact of such a system to quantitatively assess the impact of medication for PwPD might open offer improved methods to medication titration protocols.

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