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The Kinematics of Parkinson's Disease: Utilizing Foot Sensors as a Predictor of Postural Instability and Severity

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Abstract

Around 60,000 individuals are diagnosed with Parkinson's Disease (PD) in the United States each year. With the disease's increasing prevalence, early severity diagnosis is critical for effective symptom management. The MDS-UPDRS is the current gold standard of PD severity diagnosis, which is highly comprehensive. Still, it lacks the utilization of complex data, and its potential subjectivity contributes to the accuracy of only 80.6% of clinical diagnoses of PD. This research project aims to incorporate kinematic data in the MDS-UPDRS by analyzing the impact of left and right foot velocities on the Postural Stability MDS-UPDRS score and, thus, PD severity. Three primary data analyses were conducted to investigate the relationships between (1) velocity and time (i.e., constructing velocity curves), (2) step length for control and PD patients, and (3) step length and MDS-UPDRS scores. Velocity and step length demonstrated a positive correlation; the trends among participant groups in velocity curves were similar to those of the step length boxplot analyses, as confirmed by confidence intervals and p-values. Additionally, a statistically significant ($p=0.0237$) inverse relationship between step length and MDS-UPDRS scores was observed, indicating that larger step lengths correlate with better postural stability. These results culminate in a negative correlation between foot velocity and MDS-UPDRS scores, and therefore, incorporating kinematic data into the MDS-UPDRS may reduce subjectivity and improve early diagnosis accuracy. By combining this modified rating scale with other diagnostic methods, researchers can develop a device that accurately diagnoses and treats Parkinson's disease.

Key Words: Biomedical Engineering; Biomechanics; Parkinson's Disease; Gait Analysis; Foot Sensors.

Introduction

By 2030, the prevalence of Parkinson's Disease (PD) in the United States is expected to rise by 29% (Parkinson's Foundation, 2019). First identified by James Parkinson in 1817, PD is a chronic neurological disorder that primarily affects individuals around 60 years of age. The National Institutes of Health reports that between 5% and 10% of people with PD experience symptoms before age 50. A hallmark feature of PD is postural instability, which results from degeneration of dopaminergic nerve cells in the substantia nigra (Latif et al., 2021). Levodopa, the first intervention method, was developed in 1961 to stimulate dopamine activity and has been shown to improve akinesia (Tambasco et al., 2018). Another intervention method developed approximately 26 years later is deep brain stimulation, which involves using implanted electrodes to generate electrical impulses that activate specific cells and chemicals in the brain. Deep brain stimulation is effective in treating some PD symptoms, including dyskinesia caused by long-term use of Levodopa (Shin et al., 2020). However, neither treatment provides a complete cure for PD.

Scientists continue to seek accurate early diagnosis of PD and more effective strategies to halt symptom progression. This paper focuses on the relationship between kinematic data, step length, and the MDS-UPDRS scores: three variables that may offer deeper insight into disease severity and management.

Parkinson's Symptoms and Postural Instability

Parkinson's Disease (PD) is characterized by three primary motor symptoms: resting tremors, stiffness, and bradykinesia, which, along with loss of postural reflexes, are the cardinal signs of the disorder. The presence and severity of these symptoms enable clinicians to distinguish PD from other Parkinsonian syndromes (Williams & Litvan, 2013). Additional supportive diagnostic criteria include the observation of secondary motor symptoms, such as freezing of gait, dystonia, dysarthria, and sialorrhea, as well as non-motor symptoms, including sleep disorders and irregular or atypical cognitive and neurobehavioral functions (Jankovic, 2008). The absence of even a few of these symptoms suggests the presence of an alternative Parkinsonian disorder.

Postural instability (PI) is another highly debilitating feature of Parkinson's Disease (Palakurthi & Burugupally, 2019). Clinicians assess PI using the pull test, which involves pulling back on the patient's shoulders. At the same time, wearable sensors record various metrics such as time to regain balance, step length, number of steps taken, and velocities of different body parts (Chen et al., 2013). These measurements

not only provide insight into balance but also serve as kinematic indicators that could help quantify PD severity more precisely.

Analyzing PI, Gait, and Severity of PD

A patient's gait assessment is conducted using the gait test, a simple method for evaluating their normal walking ability. The patient is asked to walk along a hallway while wearable sensors gather data, as in the pull test (Pistacchi, 2017). *Note that while similar, the gait and pull tests are distinct; the former tests walking, and the latter tests balance.*

Although such tests are available, there is currently no standard diagnostic method for Parkinson's Disease (PD), and the severity of the disorder and associated symptoms is challenging to measure objectively. Presently, the rating scales used to assess the severity of PD symptoms rely heavily on subjective observations rather than complex data or numerical measurements. The primary rating scale used in clinical practice is the Movement Disorder Society-Sponsored Revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS), developed in the 1980s as an updated version of the original UPDRS and an alternative to the previously used Hoehn and Yahr Rating Scale from 1967 (Goetz et al., 2004). The MDS-UPDRS evaluates 50 symptoms across four categories: non-motor experiences of daily living, motor experiences of daily living, motor examination, and motor complications (Goetz et al., 2008). Symptoms such as postural instability are rated on a scale from 0 to 4 (Table 1). However, the reliance on subjective scoring has prompted a search for more objective, data-driven assessments.

Table 1: Section 3.12 Postural Stability from MDS-UPDRS

Score	Category	Description
0	Normal	No problems
1	Slight	Not quite erect, but posture could be normal for older person
2	Mild	Definite flexion, scoliosis or leaning to one side, but patient can correct posture to normal posture when asked to do so.
3	Moderate	Stooped posture, scoliosis or leaning to one side that cannot be corrected volitionally to a normal posture by the patient.
4	Severe	Flexion, scoliosis or leaning with extreme abnormality of posture.

TABLE 1. Section 3.12 Postural Stability from MDS-UPDRS.

PI and Kinematic Data

The MDS-UPDRS lacks precision in its examination of data, which may contribute to the clinical accuracy of PD, which is currently at only 80.6% (Rizzo et al., 2016). However, incorporating kinematic data may offer a solution to this issue. Kinematic data, including velocities, acceleration, the center of mass velocity, step length, and time, is collected during pull tests using 17 wearable sensors (Bologna et al., 2016). Currently, wearable sensors and kinematic data are utilized in two areas of Parkinson's research: long-term monitoring of motor symptoms (Borzì et al., 2019) and treatment of motor symptoms (Ileșan et al., 2022), mainly tremors. Kinematic data, particularly from foot sensors, are generally disregarded outside these two areas, with scientists attempting to establish correlations between PI and other PD factors (Błaszczyk et al., 2007) rather than with different forms of data.

Thus, a central question emerges: What relevant questions about PD can kinematic data address, and how might it improve the accuracy of PD diagnosis? This experiment aimed to identify the effect of the velocities of the left and right feet on the Postural Stability MDS-UPDRS score and, thus, on the severity of PD. The hypothesis postulated that an increase in foot velocities would correspond to a decrease in the UPDRS score. As scientific literature suggests, foot velocity positively correlates with step length, and as a longer step length can improve stability while walking, ultimately leads to a decrease in the MDS-UPDRS postural stability score.

Methods

Datasets

All datasets utilized in this study were sourced from the University of Minnesota. Kinematic data were collected during pull tests at the clinic, where patients wore 15 Inertial Measurement Units (IMUs) to record movement data through the Xsens program. Xsens utilizes this data to create a virtual representation of the body (Goulermas et al., 2008), and the IgorPro software was used to identify the onset of perturbation (Martin et al., 2006). The generated time-series kinematic data, such as the time until the balance was regained, velocities, accelerations, etc., were then extracted.

Velocity Curves

Generating velocity curves that depict the relationship between velocity and time is necessary to establish the correlation between velocity and step length. Comparisons between these velocity curves and the step length analyses of PD patients can establish the link between velocity and step length.

Data analysis was performed in R Studio using the tidyverse package suite, including dplyr, rmisc, and the ggplot2 library for data processing and visualization. After preparing the environment and preprocessing the data, the center of mass, left foot, and right foot velocity data frames were merged into one master set. To eliminate any unnecessary overlap between the two velocity curves, it was determined whether the left or right foot responded first to the perturbation. Upon filtering the master data set to contain only the first foot and center of mass velocities for control (n=54) and PD (n=61) patients, ggplot was used to create the curves. The same patients were tracked at baseline and at a twelve-month follow-up, provided they were unmedicated at both time points, yielding a sample size of 61.

The velocity curves were deemed statistically significant if their confidence intervals did not overlap for 50 milliseconds or longer.

Step Length for Control and Baseline + Twelve-Month Follow-Up PD Patients

This analysis uses the same patients (and primarily the same libraries) as the previous data analysis, and as before, the PD patients were separated into two groups. Here, the relationship between step length and the control and PD patients at baseline and twelve months is analyzed. The ggplot2 library, specifically the geom_boxplot function, was used to create the graph with a slight modification–the average step length is shown rather than the median. The statistical significance between the groups of patients was calculated using the compare means function with the Wilcoxon Signed-Rank Test.

The data analyses thus far have helped conclude the relationship between velocity and step length.

Results and Discussion

Velocity Curves

The velocity curves in Figure 1 depict the relationship between velocities and time and their respective confidence intervals. Notably, only the velocity of the first foot responding to the perturbation from the pull test is displayed. As the Figure 1 caption states, these curves are statistically significant as the confidence intervals do not overlap for at least 50 milliseconds. It is worth noting that the velocity of the right foot for PD patients at baseline and 12 months later is nearly identical. At the same time, a significant difference is observed between control and PD patients in terms of left and right foot velocities. These observations, in conjunction with Figure 2, confirm the positive correlation between foot velocity and step length.

There is, however, a noticeable difference between the left and right foot velocity curves of PD patients. This is likely due to the size of the applicable patient population; the majority appeared to first use their right foot in response to the "pull," indicating right-handedness among this participant population (Hebbal & Mysorekar, 2006).

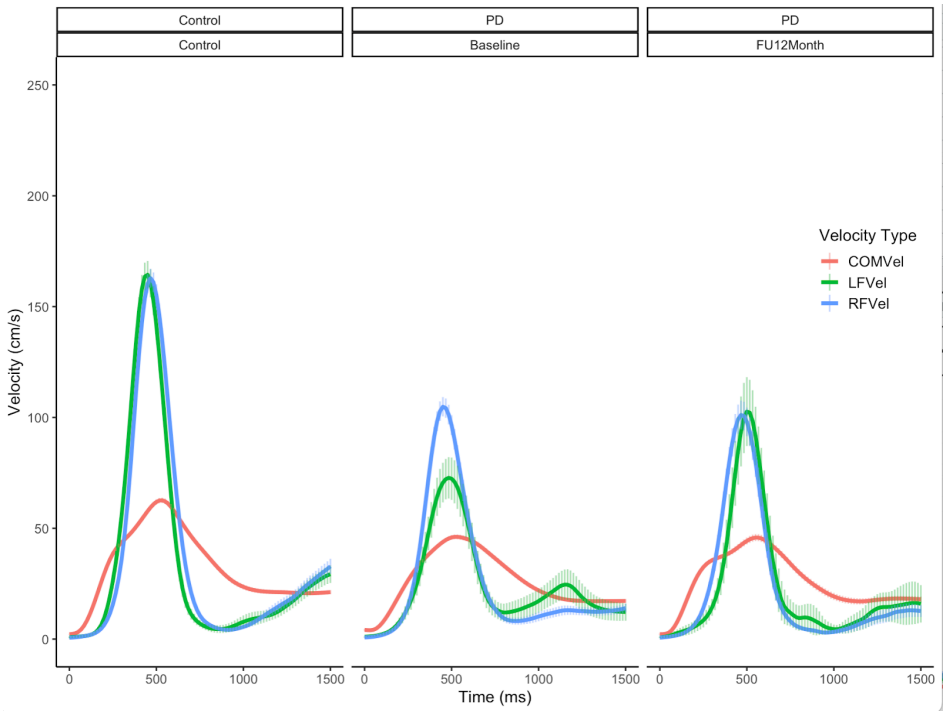

FIGURE 1. Center of mass (COMVel), left foot (LFVel), and right foot (RFVel) velocity curves for Control and PD patients, further grouped by visits. Follows first foot to move in response to perturbation from pull test. *Not all 61 PD patients are on medication at both visits.* All curves are statistically significant; the confidence intervals do not overlap for 50 ms or more considerable periods.

Step Length for Control and Baseline + Twelve-Month Follow-Up PD Patients

The boxplots in Figure 2 demonstrate the relationship between step length for control and PD patients, grouped by visits, and the mean step length is represented with a slight modification. Combined with the findings from Fig. 1, the correlation between velocity and step length becomes apparent. The p-values ($p = 0.19$) suggest that there is no significant difference between the average step lengths of PD patients at baseline and their twelve-month follow-up (similar to the lack of difference in the right foot velocities of PD patients in Fig. 1). However, there are significant differences between the baseline PD and control patients ($p = 1.71e^{-82}$) and

the PD twelve-month follow-up and control patients ($p = 1.16e^{-65}$), which is like the substantial difference in foot velocities between control and PD patients in Fig. 1. The graphs prove a positive correlation between velocity and step length.

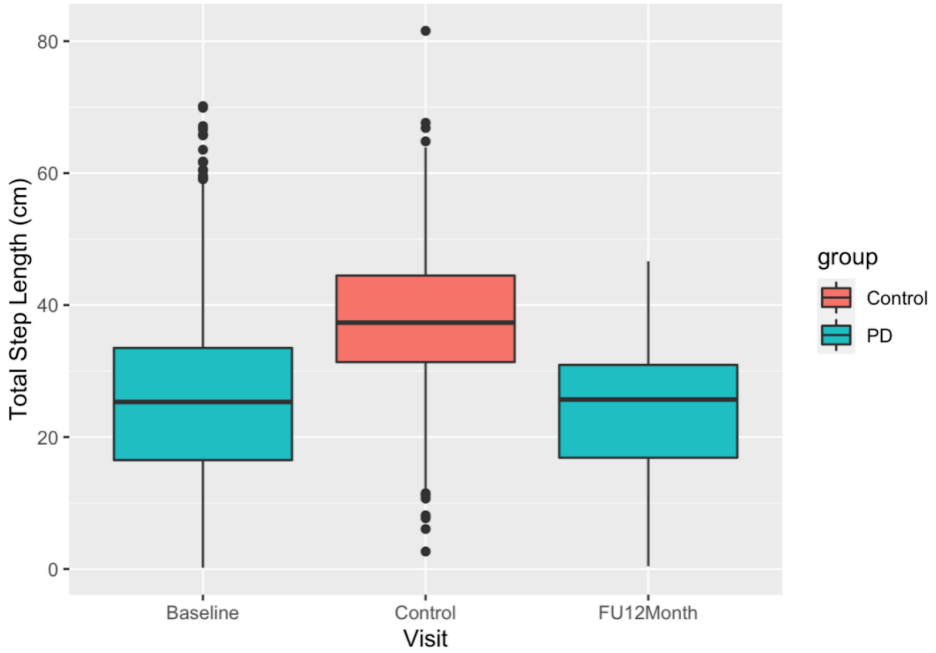

FIGURE 2. Total step length for Control and PD patients, grouped by visits. Note the lack of a statistically significant difference between the baseline and twelve-month follow-up PD patients (p-value = 0.19; greater than 0.05), but the presence of one between the PD baseline and Control patients (p-value = $1.71e^{-82}$; less than 0.05) and one between the PD twelve-month visit and Control patients (p-value = $1.16e^{-65}$; less than 0.05).

Step Length and MDS-UPDRS Postural Stability Score

The error bar line graphs of Figure 3 depict the relationship between step length and the MDS-UPDRS postural stability score, using functions such as ggplot, geom_errorbar, and geom_line. Additionally, the summary_SE function analyzed the various MDS-UPDRS scores before graphing. *All the control patients had MDS-UPDRS postural stability scores of 0 and were thus not separated from the PD patients on the x-axis.*

All relationships depicted, except for the one between MDS-UPDRS scores 2 and 3, were statistically significant with an average p-value of 0.02368. Although the relationship between scores 2 and 3 is statistically significant ($p=1.75e^{-1}$), the result may be unreliable due to the small sample size (n=5), compared to the 56 PD patients who scored 1 and 2 and the 54 control patients with a score of 0.

The data analysis strongly suggests a clear inverse relationship: lower step lengths are associated with higher (worse) scores. This reinforces the chain linking foot velocity → step length → postural stability.

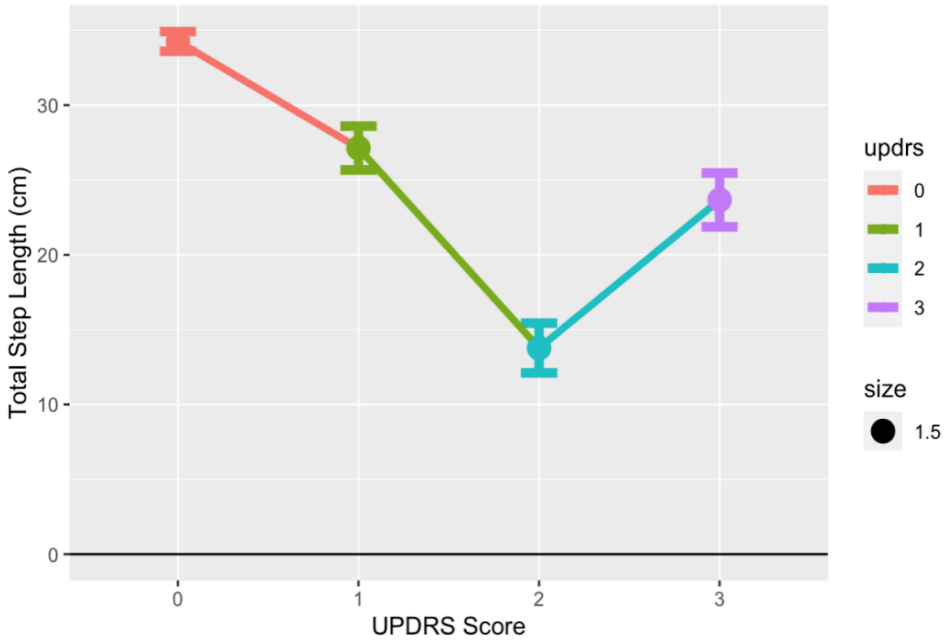

FIGURE 3. MDS-UPDRS Postural Stability scores as related to the pull test step length. Note how all the relationships (technically except between 2 and 3) are statistically significant. Between 0 and 1, $p = 7.94e^{-17}$; between 0 and 2, $p = 4.26e^{-45}$; between 0 and 3, $p = 1.04e^{-18}$; between 1 and 2, $p = 2.94e^{-23}$; between 1 and 3, $p = 1.05e^{-2}$; all are less than 0.05. While the relation between 2 and 3 is significant by definition ($p = 1.75e^{-13}$), it is an "outlier" because only five patients were recorded for scores of 3 vs. 26 for scores of 1 and 2 and 54 for scores of 0.

Conclusion

Before validating or refuting the hypothesis, two concepts need to be examined. The first is the relationship between velocity and step length, supported by scientific literature (Alvarez et al., 2006; Hubert et al., 2015), and logical reasoning. Velocity represents the distance traveled over time, and greater velocities indicate that a greater distance was covered in less time, requiring longer steps. Although one might assume that this relationship is more closely related to mass, the fact that most patients had a similar center of mass velocity supports the original idea. Connecting this concept with the established inverse correlation between step length and MDS-UPDRS Postural Stability scores confirms the hypothesis.

However, this conclusion applies primarily to right foot velocity, as the dataset lacked sufficient left foot response data. This limitation should be addressed in future studies.

Although previous studies have indicated a positive correlation between step length and the MDS-UPDRS Postural Stability scores, this relationship has yet to be explicitly described in the literature (Lai et al., 2022; Virmani et al., 2022). However, many studies have examined the relationship between step length and gait, particularly regarding the patient's walking ability (Revuelta et al., 2022). These studies have consistently demonstrated that greater step length is associated with a lower likelihood of freezing of gait, which suggests better walking ability (Quek et al., 2022). Accordingly, individuals with better walking ability would be expected to have good balance and high postural stability, as reflected in a lower MDS-UPDRS Postural Stability score.

Recent research utilizing wearable sensors has indicated the potential implications of kinematic data in accurately diagnosing the severity of Parkinson's disease (PD) (Balakrishnan et al., 2022; Rovini et al., 2017). This study contributes to that ongoing research, providing evidence that foot velocity—especially in the right foot—may serve as a useful, objective indicator of disease severity, as researchers aim to create unobtrusive devices using machine learning to diagnose, monitor, and treat PD symptoms (Mughal et al., 2022; Mei et al., 2021; Makarious et al., 2022).

Future avenues of research should explore whether integrating kinematic measurements with machine learning models or accelerometer data can further enhance clinical utility. Sample size expansion, especially for higher MDS-UPDRS scores and left foot analysis, will be critical to validating these early findings.

It is concluded that by integrating a kinematic data-enhanced rating scale with other clinical diagnosis techniques (e.g., accelerometers, force-sensitive resistors, gyroscopes, wearable sensors, etc.), practitioners can develop a comprehensive approach to diagnosing, evaluating the severity of, and effectively managing Parkinson's Disease.

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