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Falling Out of Postural Instability: Evaluating the Contribution of Somatosensation to Standing Balance in Parkinson's Disease

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ABSTRACT

People with PD (PwPD) experience a variety of motor symptoms, including postural instability, impaired gait, tremors, and falls. Falls among PwPD are especially debilitating, as they can result in fracture risk, increased progression of the disease, and even death. Previous research has demonstrated that the somatosensory system, consisting of tactile sensation (which is responsible for feelings of touch and pressure) and proprioceptive feedback (which is important in joint position sense), is crucial for reactive balance control. The primary goal of this project was to determine the unique contributions of the tactile and proprioceptive systems to standing balance control in PD. Participants at the Gait and Balance Disorders Lab at Arizona State University were asked to maintain their balance while experiencing 3 sensory vibration conditions from vibrotactile transducers 1) a control condition with no vibration, 2) vibration underneath the feet to disturb tactile sensation, and 3) vibration on top of their feet (dorsiflexor tendon) to manipulate proprioception. Another goal was to identify predictors of somatosensory impairment during standing balance (i.e., participants affected most by sensory vibration) by associating clinical characteristics with change scores in balance outcomes from the no vibration-control condition to the tactile and proprioceptive stimulation conditions. The results of this study indicate that vibrotactile stimulation had minimal impacts on standing balance responses. This study also found few predictors of somatosensory impairments. Further research is needed to enhance clinical efficiency in designing treatments that have the most impact on improving balance control and preventing falls.

Introduction

Background Literature

Parkinson's disease (PD) is a chronic neurodegenerative disorder. According to the Parkinson's Foundation, it affects "more than 10 million people worldwide," nearly one million of which are people in the United States (Parkinson's Foundation, n.d.-b). Additionally, each year, "nearly 90,000 people in the U.S. are diagnosed" with the disease (Parkinson's Foundation, n.d.-c). And these numbers are continuously increasing, making PD one of the world's fastest growing neurological disorders.

Although PD is the second-most common neurodegenerative disease in the world (Parkinson's Foundation, n.d.-b), there is still so much that remains unknown about it. Researchers do know, however, that PD involves the loss of neurons in the substantia nigra of the brain (National Institute on Aging, 2022). The substantia nigra controls a person's motor functions, thus PD is characterized by a progressive loss of motor and sensory control, resulting in symptoms like freezing of gait, tremors, and postural instability, as well as other nonmotor symptoms (National Institute on Aging, 2022).

Postural instability, or impaired balance, leads to one of the most significant health concerns: falls (Shaffer & Harrison, 2007). Falls among older adults are becoming increasingly prevalent and have severe physical, financial, and psychological consequences, including hip fractures, traumatic brain injuries, decreased quality of life, and even death (Albrecht et al., 2018). For PwPD, falls can also lead to increased progression of the disease.

The U.S. Centers for Disease Control and Prevention (CDC), a leading public health organization, reports that in 2017 alone, over 31,000 deaths were attributed to falls with a financial toll of $50 billion (Centers for Disease Control and Prevention [CDC], 2021). And by 2030, the CDC anticipates 7 fall deaths every hour, with the financial burden expected to reach $67.7 billion (CDC, 2021). These statistics apply to all older adults, but the Parkinson's Foundation, a national organization that funds and specializes in PD research, has established that a PwPD is two times more likely to fall than their neurotypical peers (Parkinson's Foundation, n.d.-a). However, even with these devastating statistics, current exercise interventions, consisting of combinations of strength, balance, and aerobic exercises, only show moderate effectiveness in reducing falls risk by approximately 15-20% (Gerards et al., 2017; Wiedenmann et al., 2023). Therefore, it is vital to understand falls to improve fall-prevention rehabilitation and relieve falls' physical, psychological, and financial burdens.

It is well documented that balance control requires input from the visual, somatosensory, and vestibular systems (Gaerlan, 2010; Horak, 2006). However, older adults and individuals with neurodegenerative disorders, like PD, experience deficits in these sensory systems, and thus they are prone to falling (Institute for Quality and Efficiency in Health Care [IQWiG, Germany], 2017; Shaffer & Harrison, 2007). When in a "well-lit environment with a firm base of support", neurotypical people rely on 70% of their somatosensory system, 10% of their vision information, 20% of their vestibular system (Horak, 2006). Since neurotypical people rely on their somatosensory system the most, it plays an important role in both reactive balance control and standing balance control (Gaerlan, 2010; Robertson, n.d.). The somatosensory system consists of two subsystems: tactile sensation, which is responsible for feelings of touch and pressure, and proprioceptive feedback, which is important in joint position sense (Kars HJ et al., 2009). As a result, loss of tactile sensation may contribute to balance deficits and increased fall risk (Meyer et al., 2004; Monaghan et al., 2021-c; Peterson et al., 2016). Unfortunately, PwPD tend to have somatosensory impairments, leading to delayed and smaller reactive balance responses (Conte et al., 2013; Monaghan et al., 2021-c). These impairments include "elevated thresholds to spatial and temporal stimuli," as well as diminished proprioception (Gorst et al., 2019).

Even though researchers know that individuals rely primarily on proprioceptive and tactile input to maintain postural control, a gap exists regarding the relative contribution of each of the subsystems in relation to standing balance. Specifically, previous studies have not shown whether tactile sensation and proprioception are equally important for standing balance in PD or if one is more important than the other. This is because previous studies manipulated the tactile and proprioceptive systems at the same time, instead of independently (Bronte-Stewart, 2002), or they have not explored somatosensation in PD (Monaghan et al., 2021-c). Other studies show mixed findings; for example, perturbing the tactile system by anesthetizing, cooling, or standing on foam surfaces have led to changes in muscle activation, so that the motor system is affected in addition to the sensory system (Fjeldstad et al., 2011; McKeon & Hertel, 2007; Oddsson et al., 2004).

Another gap this project aimed to address was identifying predictors of somatosensory deficits in standing balance. In other words, what are the identifying characteristics of PwPD who are most at risk for impairments in balance? Answering these gaps has the potential of informing clinical research and targeting fall rehabilitation in order to increase the effectiveness of exercise interventions in reducing falls risk.

Goals of the Current Research

The primary goal of this research project was to answer the question "What is the unique contribution of somatosensation to standing balance in Parkinson's disease (PD)?" Since the somatosensory system plays a crucial role in balance control, the hypothesis was that both proprioception and tactile sensation are equally critical for maintaining posture. Participants at Drs. Monaghan and Peterson's Gait and Balance Disorders Lab at Arizona State University

(ASU) were asked to maintain their balance while standing on a treadmill and feeling no vibrations, vibrations underneath their feet (to disturb tactile sensation), and vibrations on top of their feet (to manipulate proprioception) from coin-sized vibration devices. Using sway outcomes on the treadmill, specifically center of pressure and center of mass data, the speed, displacement, and area of the participants' sway was determined. To establish the unique contribution, repeated measures analysis of variance (ANOVA) were conducted to compare sway outcomes between the three conditions: 1) no stimulation, 2) tactile stimulation, and 3) proprioceptive stimulation.

Another goal of this project was to identify predictors of somatosensory impairment during standing balance in PD. This would help answer the question: "Are there factors that predict impairments in balance due to somatosensory deficits?" For example, do people that rely more on the somatosensory system for balance have increased somatosensory deficits in standing balance control? This information could help determine how much worse or better people with PD (PwPD) were after tactile and proprioceptive manipulation; and therefore, it could help identify people most at need for treatment and target the treatment methods.

The hypothesis was that people who rely more on the somatosensory system for balance have increased somatosensory deficits in standing balance control. In other words, worse tactile sensation, worse proprioception, higher somatosensory ratios, and higher disease severity is likely to correlate to greater sway area and worse balance control with sensory manipulation on the tactile and proprioceptive systems. Additionally, increased reliance on the somatosensory system during clinical balance tests, such as Modified Clinical Test of Sensory Interaction in Balance (mCTSIB), would have worse sway during tactile and proprioceptive manipulation. To determine predictors of somatosensory deficits in standing, a change score from the COP/COM treadmill data was computed from the no-sensory stimulation trials to the 1) tactile and 2) proprioceptive stimulation trials. Then, these change scores were correlated to 1) sensory ratios from mCTSIB (mobility lab) to determine somatosensory reliance, 2) UPDRS to determine disease/ symptom severity, and 3) baseline tactile and proprioceptive measures.

Method

Drs. Monaghan and Peterson recruited 25 people with neurologist-confirmed PD from the Phoenix metro area at their Gait and Balance Disorders Lab at ASU. Participants were excluded if they presented musculoskeletal impairments that affect balance and took medications that would affect balance. All participants provided consent and could opt out of the experiment at any time.

The study design for the treadmill portion of the experiment was created by Dr. Monaghan for his reactive balance study, and a similar method was used for his reactive stepping projects (Monaghan et al., 2021-a; Monaghan et al., 2022). The participants were asked to maintain their balance while standing on a split-belt instrumented treadmill and feeling 1) no vibrations, 2) vibrations underneath their feet (to disturb tactile receptors), and 3) vibrations on top of their feet, bilaterally on their dorsiflexor tendon (to manipulate proprioceptive receptors). Vibration was applied using coin-sized vibrotactile transducers (see Figure 1), which were governed by a universal controller that was controlled by software. The C-2 tactors for tactile stimulation were at a fixed frequency of ~250 Hertz (Hz), and the C-2HDLF tactors for proprioceptive stimulation were at ~ 80 Hz. These frequencies were based on previous tendon vibration research and coincide with the sensitivity of the muscle spindles (Hospod et al., 2007; McLellan, 1973; Anastasopoulos, 2020). Muscle spindles contribute to joint movement and joint position sense by informing the nervous system about the "muscle's length and velocity of contraction" (Shaffer & Harrison, 2007).

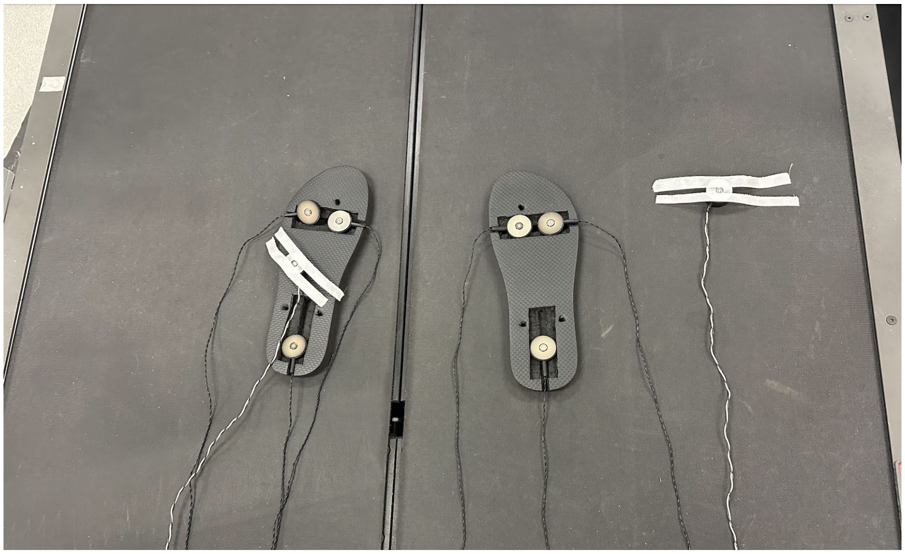

Figure 1. Insoles. Participants felt sensory vibration while standing on these insoles with coin-sized vibrotactile transducers.

The idea behind the study design was that disrupting the tactile and proprioceptive receptors in the feet and ankle during balance responses could impair balance (Robertson, n.d.; Shaffer & Harrison, 2007). In Dr. Monaghan's reactive balance study, the support surface, or treadmill (see Figure 2), would move forward causing the participants to sway backward. However, for this project, the goal was to answer the gap of the role of tactile sensation and proprioception on standing balance, so participants stood on insoles without movement from the treadmill.

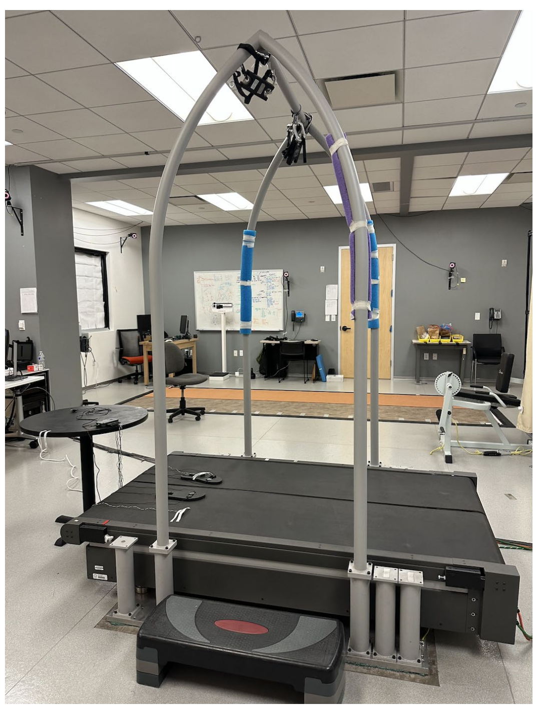

Figure 2. Treadmill. Participants stood on this instrumented split-belt treadmill with force plates underneath it.

Additionally, a 14-camera motion capture system evaluated balance. We put reflective markers on the participants, and we used infrared cameras to pick up the reflection from the markers to build a skeleton of the participant. We collected and recorded the participants' posturography, basically how much force the participant swayed with and how much time it took the participant to sway through force plates underneath the treadmill. (For a complete list of sway outcomes see Table 1 below.)

Table 1. Sway Outcome Measures and Definitions. This table is a compilation of operational definitions of sway measures included in the factor analysis. Unless otherwise noted, all measures are calculated for antero-posterior (AP) and mediolateral (ML) projections.

RMS sway (m/s^2)	Root mean square of the sway trajectory
Mean distance (m^2/s^2)	Mean distance of the lumbar's trajectory
Range of acceleration (m^2/s^2)	Total range of the lumbar's acceleration trajectory
Mean velocity (m/s)	Mean velocity of the lumbar's trajectory
Total sway area (m^2/s^5)*	Sway area, computed as the area included in the sway trajectory per unit of time
95% ellipse sway area (m^2/s^4)*	Area of the 95% confidence ellipse encompassing the sway trajectory in the transverse plane
Path length (m^2/s^2)	Total length of the lumbar's acceleration trajectory
Centroidal frequency (Hz)	Frequency of sway from the centroid of the sway power spectrum
Mean frequency (Hz)	Mean sway frequency, calculated from the lumbar's acceleration trajectory length and duration. (MF = PATH / (2 * π * DIST * trial duration))
Normalized jerk	Normalized jerk (normalized to the range of the sway trajectory's excursion and duration)
95% frequency (Hz)	95% power frequency (frequency below which the 95th percentile of total power (PWR) is present)
Frequency dispersion	Frequency dispersion

*These measures do not have AP and mediolateral ML projections.
**These definitions were compiled from Mobility Lab User's Guide by APDM

Before the treadmill intervention, demographic and clinical measurements were recorded. One of the clinical tests assessed tactile sensation using 6-set Semmes-Weinstein Monofilaments. We applied monofilaments of different thicknesses to 9 sites on the participant's foot (on their dorsum and plantar surfaces), and the participant was instructed to identify the perception and location of the touch. A low score meant that the participant had strong tactile sensation and could correctly identify the locations and sensations of the thinnest filaments. Sensory scores measured from the filament size were averaged for each foot.

Next, proprioception was measured using a lower extremity position test. After asking the participant to close his/her eyes, we moved the participant's foot across a surface to a 12 cm mark. The participant had to remember this position and try to replicate this position after his/her foot was returned to the starting point. We tested the 12 cm mark twice for each foot, and then replicated the procedure for the 22 cm mark. The difference between the marked point and the point where the participant stopped his/her foot was measured and then averaged.

Additionally, MDS-UPDRS III (Unified Parkinson's Disease Rating Scale), a motor examination, was administered to measure the participant's rigidity, kinetic tremor, and freezing of gait. MDS-UPDRS III scores were summed up for each participant in order to measure the participants' disease and symptom severity. Typically, if a participant has had PD for a longer period of time, their score is higher, showing that the participant experiences severe impairment from PD. Lower scores, in turn, show that the participant's symptoms are slight and infrequently present (U.S. Department of Veterans Affairs, 2007).

Next, FSEQ (Falls Self-Efficacy Questionnaire) asked the participant if they had a fear of falling. This questionnaire was administered to further understand the participants' symptom severity. Afterwards, we conducted the mini-BEST test to assess balance impairments in PD. The test included a 2-minute walk test around an obstacle, a Timed Up and Go Dual Task test, and a portion of the mCTSIB balance test.

Lastly, the participants took part in mCTSIB, in which the participant had to maintain their balance while standing on a firm surface (the ground) with their eyes open and then eyes closed. Afterwards, they repeated the process on a foam surface and then an inclined plane. From the sway outcomes – sway area (m^2/s^4), path length (m/s^2), mean velocity (m/s), and RMS sway (m/s^2)– sensory ratios were computed to determine the participant's reliance on their somatosensory, visual, and vestibular systems. These sensory ratios were calculated using formulas described by Federica et al. (Federica et al., 2009; Monaghan et al., 2021-b):

> "Somatosensory: Eyes Open, Firm Surface/Eyes Closed, Firm Surface.
> Visual: Eyes Open, Firm Surface/Eyes Open, Compliant Surface.
> Vestibular: Eyes Open, Firm Surface/Eyes Closed, Compliant Surface."

The value obtained for each sensory system was then converted to a percentage. These percentages indicate the relative contributions of each sensory system to balance performance.

Data and Analysis

Statistical Test

After the data collection, sway outcomes were computed from the treadmill data, including the participants' path length, center of pressure (COP) area, center of mass (COM) displacement, and COM acceleration. Repeated measures ANOVA was conducted to compare sway outcomes between the three sensory conditions: 1) no stimulation, 2) tactile stimulation, and 3) proprioceptive stimulation.

Then, for the second aim of this project, change scores were calculated from the COP/COM treadmill data from the no-sensory stimulation trials to the 1) tactile and 2) proprioceptive stimulation trials for each of the sway outcomes. GraphPad Prism was used to create 2-tailed Pearson correlations and computed r-values (or correlation coefficients), which determine the strength of the relationship between the x and y variables. The x-values were change in path length, change in AP COP range, change in COM displacement, and change in COM acceleration for both tactile to no stimulation and proprioceptive to no stimulation. The y-values were the baseline tactile, baseline proprioceptive, UPDRS III, FSEQ, Mini-BEST, and somatosensory reliance scores.

Results (First Aim)

For the first aim, we conducted 4 ANOVA tests to determine the impacts of the tactile and proprioceptive systems on standing balance, specifically in relation to path length (mm), COP sway area (mm^2), AP COM maximum displacement (mm), and AP COM maximum acceleration (mm/s^2). Firstly, the Tests of Within-Subjects Effects showed that there was no significant effect of sensory stimulation on path length, $F_{2,48} = 0.632$, $p = 0.536$. Since the p-value of 0.536 is greater than 0.05, no statistically significant effect was observed. (See Table 2 below).

Table 2. Tests of Within-Subjects Effects for Path Length. This table shows the type III sum of squares, degrees of freedom, F-statistic, p-value, partial eta squared for the sway outcome measure path length.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stim_Condition	Sphericity Assumed	.015	2	.007	.632	.536	.026
	Greenhouse-Geisser	.015	1.325	.011	.632	.475	.026
	Huynh-Feldt	.015	1.373	.011	.632	.481	.026
	Lower-bound	.015	1.000	.015	.632	.435	.026
Error(Stim_Condition)	Sphericity Assumed	.559	48	.012			
	Greenhouse-Geisser	.559	31.810	.018			
	Huynh-Feldt	.559	32.956	.017			
	Lower-bound	.559	24.000	.023			

Descriptive Statistics showed that the means of the participants' performances during standing balance across the three sensory conditions were comparable, which indicates that, generally, the three conditions produced relatively similar balance responses. The mean path length during no stimulation was 0.484 mm. The mean path length during tactile stimulation was 0.450 mm. The mean path length during proprioceptive stimulation was 0.466 mm. This was unexpected, as we hoped that the tactile and proprioceptive stimulation would lead to worse standing balance performance by manipulating the somatosensory system. (See Table 3).

Similarly, Pairwise Comparisons showed that path length between the three conditions were not statistically significant because the significance values were all greater than 0.05. The p-value for the comparison between no stimulation and tactile stimulation was 0.264, between no stimulation and proprioceptive stimulation was 0.639, and between tactile stimulation and proprioceptive stimulation was 0.423. (See Table 4).

Table 3. Descriptive Statistics for Path Length. This table shows the mean, standard deviation, and population size for path length across three vibration stimulation conditions (NS: no stimulation, TS: tactile stimulation, PS: proprioceptive stimulation).

Stim_Condition	Mean	Std. Deviation	N
Path_Length_NS	.4841325	.21743650	25
Path_Length_TS	.4498686	.13458843	25
Path_Length_PS	.4656146	.15946597	25

Table 4. Pairwise Comparisons for Path Length. This table shows the mean difference, standard error, significance, and 95% confidence interval for lower and upper bound for path length as compared between the three sensory stimulation conditions (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

(I) Stim_Condition	(J) Stim_Condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for [a]... Lower Bound	95% Confidence Interval for [a]... Upper Bound
1	2	.034	.030	.264	-.028	.096
	3	.019	.039	.639	-.062	.099
2	1	-.034	.030	.264	-.096	.028
	3	-.016	.019	.423	-.056	.024
3	1	-.019	.039	.639	-.099	.062
	2	.016	.019	.423	-.024	.056

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Lastly, the Profile Plots of Estimated Marginal Means show that the error bars of the three sensory conditions overlap, which similarly indicate that the differences between the three conditions are not statistically significant. (Figure 3.)

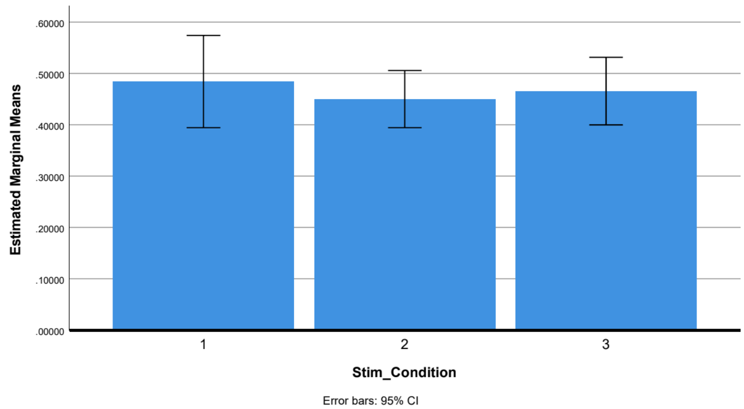

Figure 3. Profile Plots of Estimated Marginal Means for Path Length. This figure shows error bars with 95% confidence intervals for path length across the three sensory vibration conditions. Since error bars overlap, no statistically significant difference was observed. (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

I obtained similar results for COP sway area (Tables 5-7 and Figure 4), AP COM maximum displacement (See Tables 8-10 and Figure 5), and COM acceleration (See Tables 11-13 and Figure 6), in which the p-values across the ANOVA tests were statistically insignificant. The mean COP area during no stimulation was 0.0000476 mm^2. The mean COP area during tactile stimulation was 0.0000288 mm^2. The mean COP area during proprioceptive stimulation was 0.0000369 mm^2. There was no significant effect of Sensory Stimulation on COP area, $F_{2,48} = 0.760$, $p = 0.473$.

Table 5. Tests of Within-Subjects Effects for COP Sway Area. This table shows the type III sum of squares, degrees of freedom, F-statistic, p-value, partial eta squared for the sway outcome COP sway area.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stim_Condition	Sphericity Assumed	4.432E-9	2	2.216E-9	.760	.473	.031
	Greenhouse-Geisser	4.432E-9	1.142	3.882E-9	.760	.408	.031
	Huynh-Feldt	4.432E-9	1.161	3.816E-9	.760	.410	.031
	Lower-bound	4.432E-9	1.000	4.432E-9	.760	.392	.031
Error(Stim_Condition)	Sphericity Assumed	1.400E-7	48	2.916E-9			
	Greenhouse-Geisser	1.400E-7	27.402	5.107E-9			
	Huynh-Feldt	1.400E-7	27.870	5.022E-9			
	Lower-bound	1.400E-7	24.000	5.831E-9			

Table 6. Descriptive Statistics for COP Sway Area. This table shows the mean, standard deviation, and population size for COP area across three vibration stimulation conditions (NS: no stimulation, TS: tactile stimulation, PS: proprioceptive stimulation).

Stim_Condition	Mean	Std. Deviation	N
COP_Area_NS	.0000476	.00010333	25
COP_Area_TS	.0000288	.00005911	25
COP_Area_PS	.0000369	.00007026	25

Table 7. Pairwise Comparisons for COP Sway Area. This table shows the mean difference, standard error, significance, and 95% confidence interval for lower and upper bound for COP sway area as compared between the three sensory stimulation conditions (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

(I) Stim_Condition	(J) Stim_Condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for [a]... Lower Bound	95% Confidence Interval for [a]... Upper Bound
1	2	1.877E-5	.000	.370	-2.360E-5	6.114E-5
	3	1.071E-5	.000	.460	-1.871E-5	4.013E-5
2	1	-1.877E-5	.000	.370	-6.114E-5	2.360E-5
	3	-8.057E-6	.000	.362	-2.594E-5	9.824E-6
3	1	-1.071E-5	.000	.460	-4.013E-5	1.871E-5
	2	8.057E-6	.000	.362	-9.824E-6	2.594E-5

Based on estimated marginal means; a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

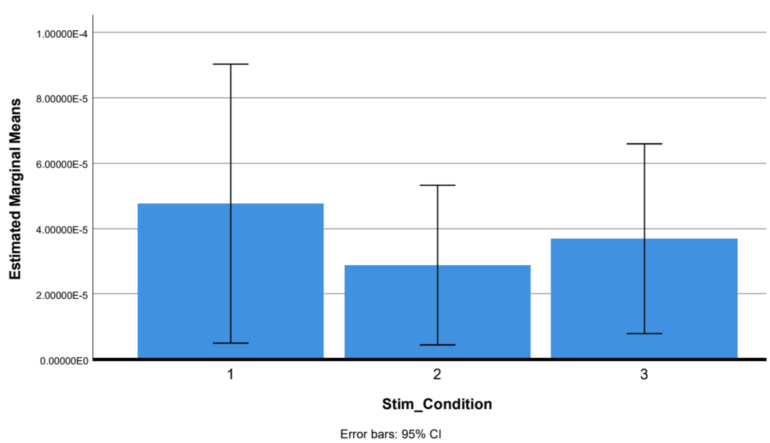

Figure 4. Profile Plots of Estimated Marginal Means for COP Sway Area. Error bars with 95% confidence intervals for COP sway area across the three sensory vibration conditions. Since error bars overlap, no statistically significant difference was observed. (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

The mean AP COM maximum displacement during no stimulation was 0.252 mm. The mean AP COM displacement during tactile stimulation was 0.252 mm. The mean AP COM displacement during proprioceptive stimulation was 0.253 mm. There was no significant effect of Sensory Stimulation on AP COM Displacement, $F_{2,48} = 0.128$, $p = 0.880$.

Table 8. Tests of Within-Subjects Effects for COM Displacement. This table shows the type III sum of squares, degrees of freedom, F-statistic, p-value, partial eta squared for COM Displacement.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stim_Condition	Sphericity Assumed	1.422E-5	2	7.109E-6	.128	.880	.005
	Greenhouse-Geisser	1.422E-5	1.461	9.733E-6	.128	.815	.005
	Huynh-Feldt	1.422E-5	1.532	9.283E-6	.128	.825	.005
	Lower-bound	1.422E-5	1.000	1.422E-5	.128	.723	.005
Error(Stim_Condition)	Sphericity Assumed	.003	48	5.537E-5			
	Greenhouse-Geisser	.003	35.061	7.580E-5			
	Huynh-Feldt	.003	36.759	7.230E-5			
	Lower-bound	.003	24.000	.000			

Table 9. Descriptive Statistics for COM Displacement. This table shows the mean, standard deviation, and population size for COM Displacement across three vibration stimulation conditions (NS: no stimulation, TS: tactile stimulation, PS: proprioceptive stimulation).

Stim_Condition	Mean	Std. Deviation	N
AP_COM_Displ_NS	.2515850	.04812470	25
AP_COM_Displ_TS	.2521320	.05087807	25
AP_COM_Displ_PS	.2526514	.05130408	25

Table 10. Pairwise Comparisons for COM Displacement. This table shows the mean difference, standard error, significance, and 95% confidence interval for lower and upper bound for COM displacement as compared between the three sensory stimulation conditions (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

(I) Stim_Condition	(J) Stim_Condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for [a]... Lower Bound	95% Confidence Interval for [a]... Upper Bound
1	2	-.001	.002	.808	-.005	.004
	3	-.001	.003	.679	-.006	.004
2	1	.001	.002	.808	-.004	.005
	3	-.001	.001	.709	-.003	.002
3	1	.001	.003	.679	-.004	.006
	2	.001	.001	.709	-.002	.003

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

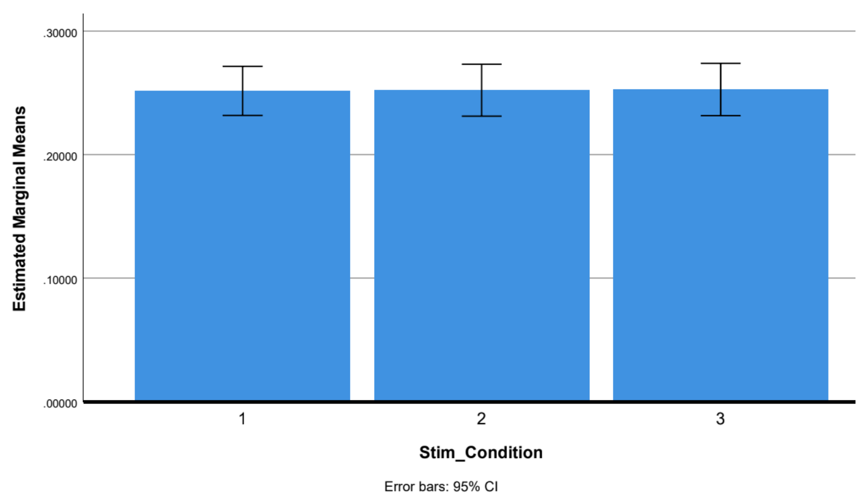

Figure 5. Profile Plots of Estimated Marginal Means for COM Displacement. This figure shows error bars with 95% confidence intervals for COM displacement across the three sensory vibration conditions. Since error bars overlap, no statistically significant difference was observed. (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

The mean AP COM maximum acceleration during no stimulation was 0.471 mm/s^2. The mean COM acceleration during tactile stimulation was 0.445 mm/s^2. The mean COM acceleration during proprioceptive stimulation was 0.452 mm/s^2.There was no significant effect of Sensory Stimulation on COM acceleration, $F_{2,48} = 0.009$, $p = 0.991$. Thus, the results of this first project goal are inconclusive, and they refute the hypothesis.

Table 11. Tests of Within-Subjects Effects for COM Acceleration. This table shows the type III sum of squares, degrees of freedom, F-statistic, p-value, partial eta squared for COM Acceleration.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stim_Condition	Sphericity Assumed	.009	2	.004	.009	.991	.000
	Greenhouse-Geisser	.009	1.771	.005	.009	.985	.000
	Huynh-Feldt	.009	1.901	.005	.009	.989	.000
	Lower-bound	.009	1.000	.009	.009	.924	.000
Error(Stim_Condition)	Sphericity Assumed	22.962	48	.478			
	Greenhouse-Geisser	22.962	42.497	.540			
	Huynh-Feldt	22.962	45.635	.503			
	Lower-bound	22.962	24.000	.957			

Table 12. Descriptive Statistics for COM Acceleration. This table shows the mean, standard deviation, and population size for COM acceleration across three vibration stimulation conditions (NS: no stimulation, TS: tactile stimulation, PS: proprioceptive stimulation).

Stim_Condition	Mean	Std. Deviation	N
AP_COM_ACC_NS	.4706621	.51536576	25
AP_COM_ACC_TS	.4446990	.56030195	25
AP_COM_ACC_PS	.4521152	.96921095	25

Table 13. Pairwise Comparisons for COM Acceleration. This table shows the mean difference, standard error, significance, and 95% confidence interval for lower and upper bound for COM acceleration as compared between the three sensory stimulation conditions (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

(I) Stim_Condition	(J) Stim_Condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for [a]... Lower Bound	95% Confidence Interval for [a]... Upper Bound
1	2	.026	.157	.870	-.298	.350
	3	.019	.209	.930	-.413	.451
2	1	-.026	.157	.870	-.350	.298
	3	-.007	.215	.973	-.452	.437
3	1	-.019	.209	.930	-.451	.413
	2	.007	.215	.973	-.437	.452

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

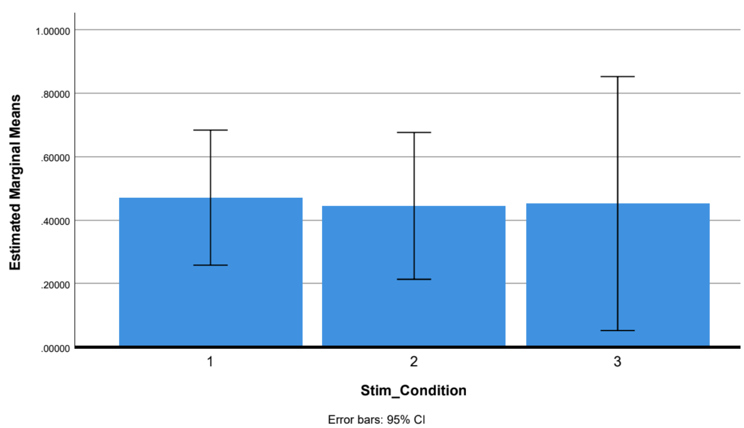

Figure 6. Profile Plots of Estimated Marginal Means for COM Acceleration. This figure shows error bars with 95% confidence intervals for COM acceleration across the three sensory vibration conditions. Since error bars overlap, no statistically significant difference was observed. (1: no stimulation, 2: tactile stimulation, 3: proprioceptive stimulation).

Results (Second Aim)

Minimal effects of sensory stimulation on standing balance responses were observed in the first aim of this project; however, change score calculations showed that some participants actually did perform better with no stimulation compared to the tactile and proprioceptive stimulation trials. This led to the development of the second aim: identifying predictors of participants affected most by sensory vibration. (See Figure 7 for the means and variability of the participants' sway outcomes.)

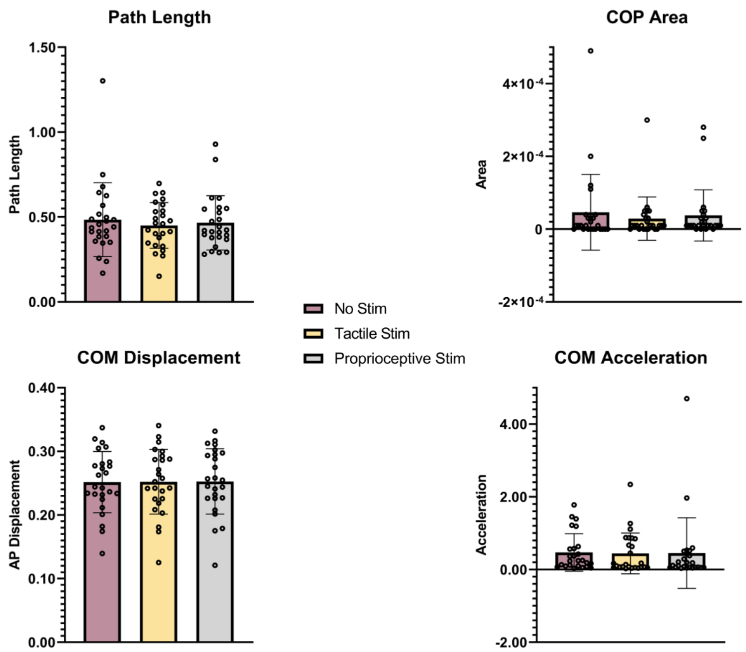

Figure 7. Means and Variability. This figure shows the means and variability of the participants' performances between the three sensory stimulation trials, displaying that there were participants who performed worse, or even better, in the tactile and proprioceptive stimulation conditions compared to no stimulation.

For the second aim of this project, only 4 out of the 36 correlations had significant or nearly significant p-values, relatively strong r-values, and made logical sense. These four correlation plots (see Figures 8-11) showed that participants that were most affected by tactile stimulation had more somatosensory reliance and worse proprioception, and that participants that were most affected by proprioceptive perturbation had worse symptom severity and worse mini-BEST balance.

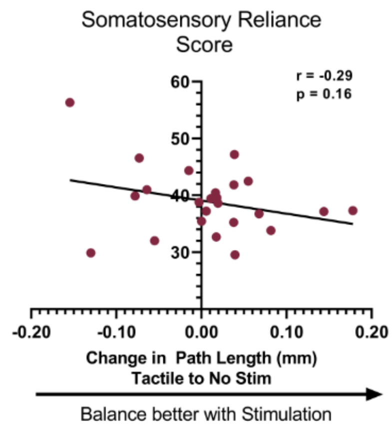

Figure 8. Somatosensory Reliance vs. Balance Correlation Plot. This correlation plot shows that participants who have a greater reliance on their somatosensory system tend to have more pronounced somatosensory deficits, or worse balance. The x-axis in the positive direction shows that balance improved with stimulation, and the y-axis in the positive direction shows higher somatosensory reliance. The x-value was calculated from the change score between the no-sensory stimulation trial to the tactile stimulation trial for the sway outcome measure of path length. Somatosensory reliance was calculated from the formula "Eyes Open, Firm Surface/Eyes Closed, Firm Surface" mentioned in the methods section, and it reveals the participants' percentage of reliance on their somatosensory system. This correlation is nearly statistically significant (p = 0.16 > 0.05) and has a negative moderate to low strength (r = -0.29).

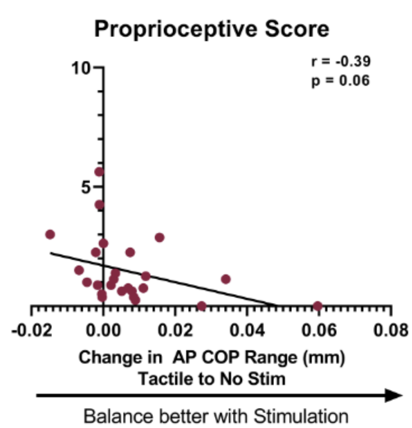

Figure 9. Proprioceptive Score vs. Balance Correlation Plot. The negative trend shows that worse balance correlates with worse proprioception. The y-axis in the positive direction shows a higher proprioceptive score. The x-value was calculated from the change score between the no-sensory stimulation trial to the tactile stimulation trial for the sway outcome measure of AP COP range. This correlation has a trending p-value (p = 0.06 > 0.05) and has a negative moderate strength (r = -0.39).

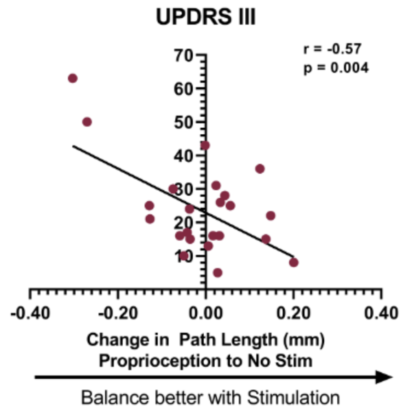

Figure 10. UPDRS III vs. Balance from Path Length Correlation Plot. Worse balance is associated with worse symptom severity. The y-axis in the positive direction shows higher UPDRS III scores, indicating worse disease severity. The x-value was calculated from the change score between the no-sensory stimulation trial to the proprioceptive stimulation trial for the sway outcome measure of path length. This correlation is statistically significant (p = 0.004 < 0.05) and has a negative moderate to high strength (r = -0.57).

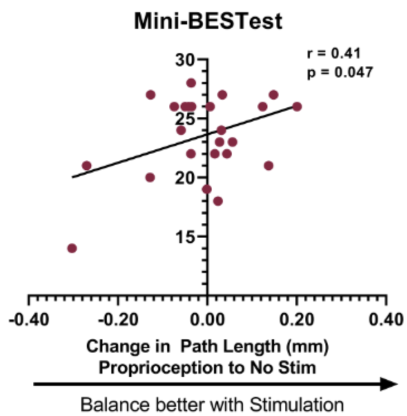

Figure 11. Mini-BEST Balance vs. Treadmill Balance Correlation Plot. Worse mechanical balance (measured from the treadmill) correlates with worse clinical balance (measured from mCTSIB). The y-axis in the positive direction shows better balance. The x-value was calculated from the change score between the no-sensory stimulation trial to the proprioceptive stimulation trial for the sway outcome measure of path length. This correlation is statistically significant (p = 0.047 < 0.05) and has a positive moderate strength (r = 0.41).

A few examples of correlations that did not make much logical sense but had trending or significant p-values include the correlation between worse balance and lower fear of falling (Figure 12) and the one between worse balance and better disease severity (Figure 13).

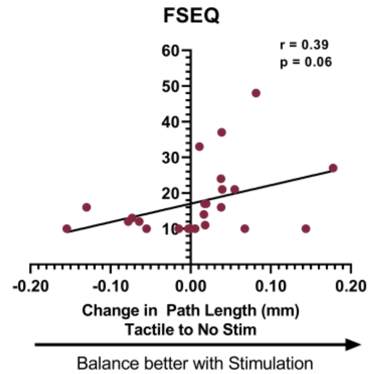

Figure 12. FSEQ vs. Balance Correlation Plot. Worse balance correlates with lower fear of falling (measured from FSEQ). The y-axis in the positive direction shows higher fear of falling. The x-value was calculated from the change score between the no-sensory stimulation trial to the tactile trial for the sway outcome measure of path length. This correlation has a trending p-value (p = 0.06 > 0.05) and has a positive moderate strength (r = 0.39). However, it does not make logical sense because typically those with worse balance have a higher fear of falling.

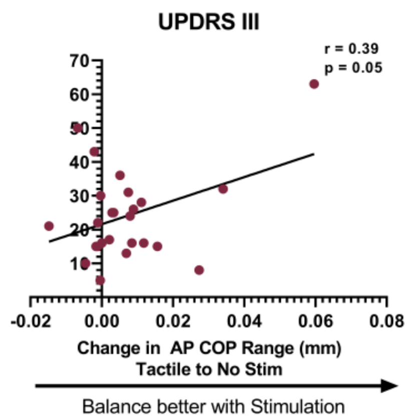

Figure 13. UPDRS III vs Balance from AP COP Range Correlation Plot. Worse balance correlates with better disease severity. The y-axis in the positive direction shows higher UPDRS III scores, indicating worse disease severity. The x-value was calculated from the change score between the no-sensory stimulation trial to the tactile stimulation trial for the sway outcome measure of AP COP range. This correlation is statistically significant (p = 0.05 = 0.05) and has a positive moderate strength (r = 0.39). Nonetheless, this correlation refutes the conclusion made by Figure 10, and it also does not make logical sense.

Discussion & Conclusion

The results for the first aim of this project were inconclusive due to the statistically insignificant p-values. This refuted the hypothesis that proprioception and tactile sensation are critical for maintaining standing balance, because the stimulation had minimal effects on the participants. Thus, the relative importance of the tactile and proprioceptive systems to standing balance control in PD remains unclear. Despite inconclusive findings, this project furthers our knowledge on the role of somatosensation in standing balance control in PwPD. For the second aim, it was found that with tactile stimulation worse balance correlates with greater somatosensory reliance and worse proprioception. Furthermore, this project discovered that from proprioceptive stimulation, worse balance correlates to worse disease severity and worse balance from the mini-BEST, a clinical balance test.

Future Research

These conclusions highlight the importance of future research on the somatosensory system. For future research, researchers could aim to find and refine sensory measures in order to determine the optimal amount of stimulation needed to perturb the somatosensory system. Moreover, researchers could conduct an in-depth analysis of the role of the vestibular system and the visual system on standing balance responses, as well as reactive balance responses. Researchers could also replicate this study in larger samples to generalize it to a larger group. In concluding whether the tactile or proprioceptive system is more important, researchers and clinicians can identify people most at need for treatment and identify targets for the balance exercises. Furthermore, they could determine if it is possible to improve these systems; and if it is possible, then they could determine if it helps with balance. Although it is evident that the somatosensory system is important in balance, it is still necessary to study it more rigorously.

Limitations

The insignificant findings could potentially be due to the fact that the somatosensory manipulation from the vibrotactile transducers did not sufficiently target the participants' tactile and proprioceptive systems past their individual sensory stimulation thresholds. However, the stimulation intensity was maximized to the range of the hardware. Because multiple sensory systems are implicated in balance, another reason could be that other sensory systems, like the vestibular system or the visual systems, play a larger role in standing balance compared to the somatosensory system. In fact, sensory ratios calculations from the mCTSIB test indicated that the participants in this study generally relied the most on their visual systems, then their somatosensory systems, and the least on their vestibular systems. For example, for path length, participants, on average, had a 42% reliance on their visual system, 39% on somatosensory, and 19% on vestibular. This could be since PwPD have somatosensory deficits, causing them to rely more on their other sensory systems to maintain balance.

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