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Altered kinematics of arm swing in Parkinson's disease patients indicates declines in gait under dual-task conditions

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ABSTRACT

Objective: Declines in simultaneous performance of a cognitive and motor task are present in Parkinson's disease due to compromised basal ganglia function related to information processing. The aim of this project was to determine if biomechanical measures of arm swing could be used as a marker of gait function under dual-task conditions in Parkinson's disease patients.

Methods: Twenty-three patients with Parkinson's disease completed single and dual-task cognitive-motor tests while walking on a treadmill at a self-selected rate. Multiple cognitive domains were evaluated with five cognitive tests. Cognitive tests were completed in isolation (single-task) and simultaneously with gait (dual-task). Upper extremity biomechanical data were gathered using the Motek CAREN system. Primary outcomes characterizing arm swing were: path length, normalized jerk, coefficient of variation of arm swing time, and cognitive performance.

Results: Performance on the cognitive tasks were similar across single and dual-task conditions. However, biomechanical measures exhibited significant changes between single and dual-task conditions, with the greatest changes occurring in the most challenging conditions. Arm swing path length decreased significantly from single to dual-task, with the greatest decrease of 21.16%. Jerk, characterizing smoothness, increased significantly when moving from single to dual-task conditions.

Conclusion: The simultaneous performance of a cognitive and gait task resulted in decrements in arm swing while cognitive performance was maintained. Arm swing outcomes provide a sensitive measure of declines in gait function in Parkinson's disease under dual-task conditions. The quantification of arm swing is a feasible approach to identifying and evaluating gait related declines under dual-task conditions.

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1. Introduction

Parkinson's disease (PD) is a neurodegenerative disorder resulting from loss of dopaminergic cells in the substantia nigra. Diminished dopamine reduces effectiveness of the basal ganglia-thalamocortical circuits, resulting in loss of motor, associative/cognitive, and limbic functions. Typical disease manifestation resulting from circuit disruption is marked by four cardinal physical symptoms - resting tremor, bradykinesia, rigidity and postural instability. Typically observed gait-related changes include stooped posture, shuffling gait, reduced arm swing, reduced stride-length and decreased joint range of motion [1]. Of these markers of gait dysfunction, decreased arm swing is most commonly reported [1].

Parkinson's disease related changes in arm swing include decreased range of motion, decreased acceleration, and increased asymmetry between limbs [2,3] during gait. In healthy individuals, the reciprocal control of arm swing and leg movements during walking is neurally coupled, and likely controlled by central pattern generators [4]. The successful performance of gait is characterized by the integration of both spinal cord output and higher level executive processes [4]. Parkinson's disease disrupts these neural circuits [5], resulting in gait impairments; however, it is not well understood how the executive control processes in conjunction

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with central pattern generator circuits are affected. Previous studies have provided insight on possible mechanisms for arm swing decline in PD gait, such as the sub-thalamic nucleus preferentially activating the lower extremities over the upper [6], and have been shown to worsen with increasing cognitive demands (i.e. dual-task (DT)) [7].

Dual-task paradigms provide a method to evaluate and manipulate the process of allocating executive function resources and their overall capacity. During cognitive-motor DT activities, increases in attentional demands necessitate greater utilization of executive function to manage the increased cognitive load. Predictably, increased task complexity reflects increased prefrontal cortical activity [4,8]. The allocation of additional resources to a difficult cognitive task disrupts normal gait function in older adults and PD patients [8]. Healthy older adults exhibit significant decreases in DT gait performance, characterized by changes in step velocity, step time, step length [9] and increased arm swing asymmetry [10]. Individuals with PD generally exhibit even greater DT costs (DTC) than healthy peers, including decreases in joint range of motion, step length and width, and cadence, as well as increases in asymmetry and variability [9,11–13].

Gait related declines in PD defined by lower extremity measures are well characterized [9,11–13]. However, these measures can be difficult to acquire and process. Understanding DT declines associated with PD using arm swing is not well established, especially under various conditions requiring different types of cognitive processing.

It was hypothesized that cognitive loads accessing different cognitive domains of variable difficulty would elicit declines in arm swing motion in people with PD under DT conditions. It was predicted that path length, normalized jerk and coefficient of variation of arm swing time (cvAST) would be appropriate metrics to accurately quantify changes in quality of movement relating to cognitive resource allocation.

2. Methods

2.1. Study design

A prospective research study was conducted investigating the effects of single-task (ST) and DT cognitive-motor interventions on changes in cognitive function and gait. All participants completed the informed consent process approved by the Institutional Review Board of Cleveland prior to data collection.

2.2. Participants

Twenty-four participants were recruited from the Cleveland Clinic Center for Neurological Restoration; one participant was unable to complete cognitive testing and was excluded from analysis. The remaining 23 participants were included in analysis. Inclusion criteria were as follows: adults with idiopathic PD, Hoehn and Yahr stage 2–4, able to ambulate >300 feet with or without use of an assistive device. Exclusion criteria included: deep brain stimulation or other PD-specific surgical intervention, musculoskeletal injury or neurological disease other than PD that would restrict ambulation, inability to follow two-step commands, and three or more errors on the Short Portable Mental Status Questionnaire [14]. All participants were tested one hour after taking their anti-Parkinsonian medications to ensure testing during "on" state. No participant used an assistive device.

2.3. Equipment

Biomechanical data were gathered using the Computer Assisted Rehabilitation Environment (CAREN) system (MotekforceLink, Amsterdam, Netherlands) located on the Cleveland Clinic's main campus. The CAREN system is an integrative motion capture system; consisting of a 10-camera Vicon system (Vicon Inc., Oxford, UK), a treadmill (Bertec Corp., Columbus, Ohio), 180-degree cylindrical projection screen system, and D-Flow software (MotekforceLink, Amsterdam, Netherlands). The Human Body Model (HBM) is a feature of the D-Flow software, which uses the 3D position of 14.00 mm retroreflective markers to calculate biomechanical gait parameters [15]. A set of 25 markers were placed by the same clinician according to the HBM (Fig. 1) [15]. Six additional markers (31 total) were placed bilaterally on the acromioclavicular process of the shoulder, ulnar process of the elbow, and the dorsal side of the wrist to measure arm swing. Position data were sampled at 100 Hz.

Walking speed was selected using the CAREN system "self-paced" feature. A self-paced treadmill speed algorithm, incorporating anterior-posterior pelvis position relative to the center of the treadmill, was used for all walking tests [16]. Participants were instructed to walk at a comfortable pace and were given a 5-minute warm-up period to acclimate to the self-paced treadmill before data collection was initiated. An image of a path progressing at the speed of the treadmill was projected onto the screen to simulate over-ground walking, and the treadmill remained at 0% grade throughout the trial. The treadmill was equipped with a non-restrictive harness and handrails, and participants wore comfortable walking shoes.

2.4. Procedure

Prior to biomechanical gait data collection, each participant completed the following tasks in a seated position to evaluate cognitive function under single-task (ST) conditions: N-back test evaluating working memory [17], serial-7 subtraction challenging attention and concentration, digit recall focusing on attention and working memory, verbal fluency evaluating semantic memory, and visual Stroop test looking at processing speed and attention. A two-minute duration was used for the ST walking and serial-7 subtraction task for comparison to the standardized 2-minute walk test. Verbal fluency was conducted using a 60-second trial. The N-back and Stroop tests were presented visually on the projection screen with letters or words displayed on the screen every two seconds during a 60-second trial [18]. All other tasks utilized auditory presentation, and were provided by the same test technician. Duration for the digit recall task was variable depending on the correct responses from the participant. The order of cognitive tasks under ST conditions was randomized across participants, via random number generator.

After the ST cognitive testing and the familiarization period on the self-paced treadmill, the cognitive tasks, in same order as the ST conditions, were performed while participants walked on the treadmill (DT). Participants were instructed to walk at a comfortable pace and were not instructed to prioritize one task over another. Following completion of all DT walks, a 2-minute ST walk was completed. Rest breaks were given between dual-task assessments as requested by the participant.

2.5. Biomechanical variables

Biomechanical data were parsed into the more affected (greatest symptom presentation in upper and lower extremities per MDS UPDRS-III) and less affected (least symptom presentation) sides.

Markers placed on the approximate center of the wrist were used to measure displacement during arm swing. The raw X, Y, Z coordinates were normalized to the pelvis to provide displacement relative to the body to account for variable subject locations within the motion capture volume [15]. Arm swing was normalized by
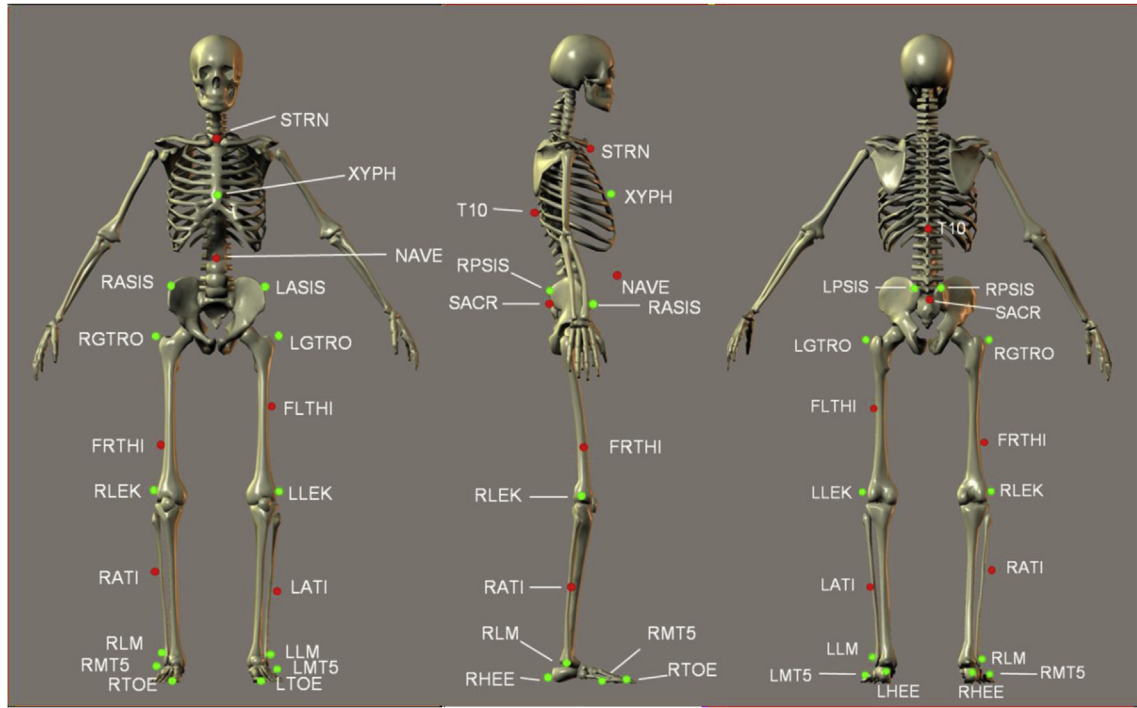
Fig. 1. Anatomical placement of motion capture markers. T10 = 10th thoracic vertebrae, SACR = sacrum bone, NAVE = navel, XYPH = xiphoid process, STRN = jugular notch of sternum, LASIS = left anterior superior iliac spine, RASIS = right anterior superior iliac spine, LPSIS = left posterior superior iliac spine, RPSIS = right posterior superior iliac spine, LGTRO = left greater trochanter of the femur, FLTHI = left thigh, LLEK = left lateral epicondyle of the knee, LATI = left anterior of the tibia, LLM = left lateral malleolus of the ankle, LHEE = left heel, LTOE = left big toe, LMT5 = left 5th metatarsal, RGTRO = right greater trochanter of the femur, FRTHI = right thigh, RLEK = right lateral epicondyle of the knee, RATI = right anterior of the tibia, RLM = right lateral malleolus of the ankle, RHEE = right heel, RTOE = right big toe, RMT5 = right 5th metatarsal.

subtracting the pelvis center (average X,Y,Z coordinates of the four iliac crest markers) from the X,Y,Z coordinates measured from each wrist marker. From the relative displacement, path length (PL) and normalized jerk (NJ) for each arm swing (defined from maximum position in anterior position to the subsequent maximum anterior position) were calculated. A minimum of 25 continuous cycles per trial were required to be included in analysis, actual cycles collected ranged from 26 to 209, averaging 78.3 ± 34.4 cycles per trial. The marker signals were filtered using a 2nd order Butterworth filter with a cutoff of 1.25 Hz, and the 3-dimensional PL was computed from the right and left hand markers using the 'arclength' Matlab function [19]. Normalized jerk was computed using the following formula to provide a measurement of smoothness of movement [20]:

$$\left(0.5 \int_{t_1}^{t_2} x^{\cdots}(t)^2 dt \right) \times \left(\frac{t^5}{L^2} \right) \tag{1}$$

Several jerk-based equations have been used to characterize smoothness of movement [7,21]. A dimensionless measure was selected to allow for comparison across trials varying by time and movement amplitude [20].

Coefficient of variation was used to characterize variability of arm swing time [22].

$$cv(AST) = \frac{SD}{Mean} \times 100 \tag{2}$$

2.6. Cognitive variables

Dual-task cost is a measure of decline observed under DT conditions. This was used for comparison amongst different cognitive tasks [23].

$$DTC[\%] = \frac{(ST \ score - DT \ score)}{ST \ score} \times 100 \tag{3}$$

2.7. Statistical analysis

All statistical analysis was completed using Origin software (OriginLab Corporation, Northampton, Massachusetts). A two-way repeated measures ANOVA was used to evaluate each arm swing variable (PL, NJ, and cvAST) and assess main effects of side (more and less-affected) and task conditions (ST, 0-Back, 1-Back, 2-Back, digit recall, serial 7, Stroop, and verbal fluency), and the interaction of side and task conditions. A Mauchly's test of sphericity was performed to ascertain the corrected p-value for the task conditions for the within-subjects analysis. Greenhouse-Geisser corrections were used. Where significant differences were found, a Dunnett's post hoc correction was used to compare each DT to the ST. A Pearson's correlation was used to determine the relationship between average velocity and arm swing PL. Paired-T tests were used to determine differences in cognitive test scores from ST to DT, and one-way repeated-measures ANOVA was used to assess differences in DTC of the cognitive test scores between different tests.

3. Results

3.1. Participants

Twenty-three participants completed the study. Participant demographics are included in Table 1.

Table 1
Participant demographics, range and mean ± SD.

Demographics	Range	Mean ± SD
Sex	12 female, 11 male	
Age (years)	51–76	63.65 ± 7.0
Disease Duration (years)	0.50–15.50	6.24 ± 4.0
Hoehn & Yahr	1–3	2.2 ± 0.5
MDS-UPDRS-Motor Score	16–64	33.0 ± 13.1
MDS-UPDRS-Gait Score	0–2	0.83 ± 0.58
Levodopa Equivalency (LEDD)	200–1300	598.18 ± 277.42
Arm Length (m)	0.43–0.55	0.50 ± 0.04
Leg Length (m)	0.69–0.84	0.77 ± 0.02
Height (cm)	154.90–186.10	169.49 ± 9.35
Weight (kg)	52.10–118.20	75.58 ± 16.76
Body Mass Index	19.46–36.85	26.19 ± 4.84
Number of Falls (past year)	0–40	3.87 ± 8.98

3.2. Cognitive performance was maintained from single to dual-task conditions

Cognitive performance showed no significant differences between the ST and DT for any of the tasks. Results provided in Table 2. There were no significant differences in DTC between any of the tasks.

3.3. Arm swing path length

Fig. 2 illustrates the path of the wrist markers for the ST (Fig. 2 A) and the 2-Back DT (Fig. 2 B) in the sagittal plane for a typical participant whose right side is more affected. Similar patterns of movement are seen in the left and right arms in the ST condition followed by a noticeable decrease in distance traveled for the DT condition. Results provided in Table 2. Analysis revealed a significant main effect of task, $F(3.62, 79.58) = 4.24$, $p < .01$, with post-hoc pairwise analysis showing a significant decrease in PL from ST to DT in the 2-back condition (21.16%, $t = 0.016$ $p < .05$) and the serial-7 condition (18.73%, $t = 0.043$ $p < .05$) (Fig. 3 A.). No significance was found in the main effect of side, nor in the interaction effect.

The relationship between arm swing PL and gait velocity was investigated. No significant correlation was found for either the MA arm ($r = 0.11$ $p = .15$) nor the LA arm ($r = 0.07$ $p = .34$).

3.4. Normalized jerk

Significant increases in NJ, (i.e worsening in arm swing smoothness), were found when comparing ST to DT (Fig. 3 B). Results provided in Table 2. Analysis revealed a significant main effect of task, $F(4.05, 89.11) = 3.75$, $p < .05$, with pairwise analysis showing a significant increase in the digit recall condition (37.06%, $t = 0.014$ $p < .05$), the serial-7 condition (41.03%, $t = 0.005$, $p < .05$), and the verbal fluency condition (31.96%, $t = 0.047$ $p < .05$). No significance was found in the main effect of side, nor in the interaction effect.

### 3.5. Coefficient of variability of arm swing time

No significant changes in cvAST were found, results listed in Table 2.

4. Discussion

Significant decreases in arm swing PL and increases in NJ detected under various DT conditions suggest that this measure of gait function is adversely affected when cognitive resources are sufficiently taxed. Our results support this hypothesis and are

Table 2
Results of main outcomes and cognitive test scores. Path length (m) (PL), normalized jerk (NJ), coefficient of variability of arm swing time (cvAST). Mean±(SD) arm swing data from each side is collapsed, statistically significant worsening from ST to DT denoted by *, p = .05.

	ST	0-back	1-back	2-back	Serial-7	Digit Recall	Stroop	Verbal Fluency
PL	0.53 ± 0.36	0.46 ± 0.33	0.47 ± 0.34	0.42 ± 0.33*	0.43 ± 0.33*	0.46 ± 0.36	0.46 ± 0.33	0.47 ± 0.35
NJ	1615.25 ± 614.14	1951.23 ± 1086.84	1948.64 ± 1067.34	2026.43 ± 1168.97	2277.95 ± 1531.10*	2213.85 ± 1410.47*	1893.22 ± 1052.23	2131.45 ± 1460.72*
cvAST	6.46 ± 7.96	6.48 ± 8.14	7.50 ± 8.56	8.00 ± 9.11	9.39 ± 8.53	7.86 ± 8.34	7.73 ± 8.20	8.68 ± 8.62
ST Cognitive Test Score		29.87 ± 0.63	28.87 ± 0.34	23.52 ± 4.54	25.78 ± 14.38	6.39 ± 1.12	28.96 ± 1.87	16.17 ± 4.61
DT Cognitive Test Score		29.96 ± 0.21	28.61 ± 1.30	25.09 ± 3.76	27.04 ± 16.57	6.00 ± 1.38	29.00 ± 1.31	15.35 ± 3.71
Cognitive Test Score DT Cost		0.32 ± 1.54	−0.89 ± 4.57	12.89 ± 43.05	13.85 ± 61.13	−5.06 ± 19.89	0.34 ± 3.34	1.20 ± 31.36
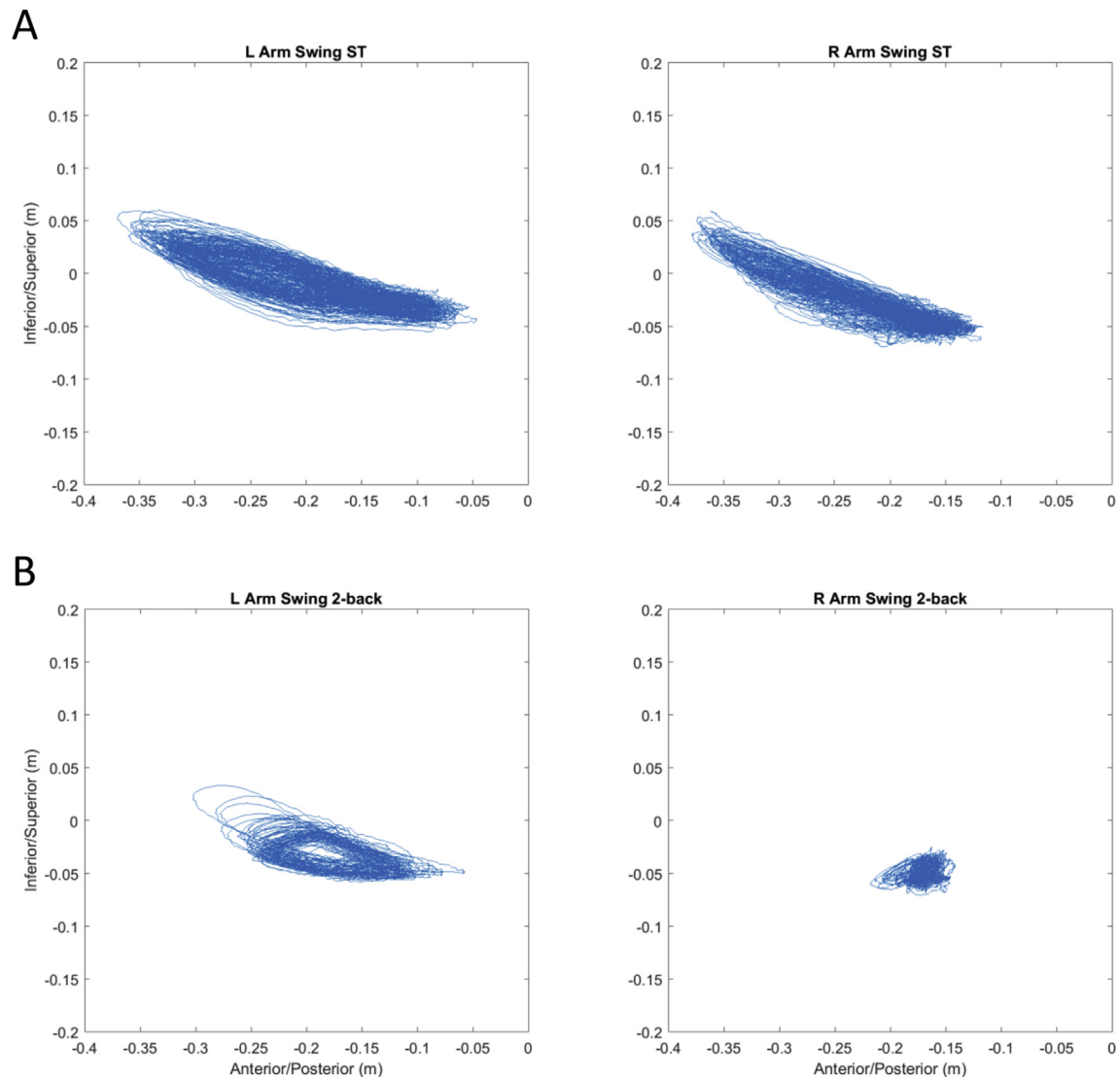
Fig. 2. Arm swing path. Example of left and right arm swing path for a ST (A) and a DT (B) trial in the sagittal plane.

consistent with other studies in terms of changes in arm swing under DT conditions, specifically decreases in arm swing magnitude and increases in jerk [7]. Our novel findings that arm swing metrics are affected by only a portion of the cognitive tests assessed expands upon the literature by examining changes in arm swing function as it relates to changes in cognitive processing across various cognitive domains. The choice of cognitive tasks was based on results from previous studies showing that these particular cognitive tests, characterizing specific aspects of executive function, are sensitive for detecting impairments in PD patients [18,23].

Although arm swing has previously been viewed as a passive result of torso rotation [24], more recent studies have shown muscular activation patterns suggesting elements of activated movement control, rather than passive, resultant movement in healthy adults [25,26]. As a participatory characteristic of gait, arm swing magnitude typically correlates positively with walking speed [24]. Arm swing amplitude has been shown to decrease under DT conditions, along with gait speed, attributing the decrease in arm swing to change in speed [27]. In this project, there was no correlation between gait speed and arm swing PL; therefore, decreases in arm swing cannot be attributed to decreased gait speed.

Moreover, changes in arm swing are indicative of other factors affecting gait, such as increased cognitive load, and may serve as an easily accessible, sensitive measure of alterations in gait function.

Changes in gait function that can lead to instability and falls are particularly concerning with a PD population. Decreased arm swing with PD is associated with increased fall risk [28], and may serve as an indicator of instability. The decrease in average arm swing PL under DT conditions in this study affected both the more- and less-affected arms, suggesting that the decrease in stability associated with the lack of arm swing is bilateral. Decreased arm swing among people with PD is notable on its own, but the greater decrease when cognitive loading increases is particularly concerning as many activities of daily living include ambulating while simultaneously focusing on a cognitive task.

In addition to decreased arm movement, increased cognitive loading results in changes in movement quality measured by NJ. Previous studies have shown jerk to be a sensitive measure to differentiate PD from controls [29] and track progress in stroke rehabilitation [30], but have not shown differences in jerk measures of arm swing in PD under DT conditions [7,21]. By employing multiple cognitive tasks of varying difficulty in this study protocol,
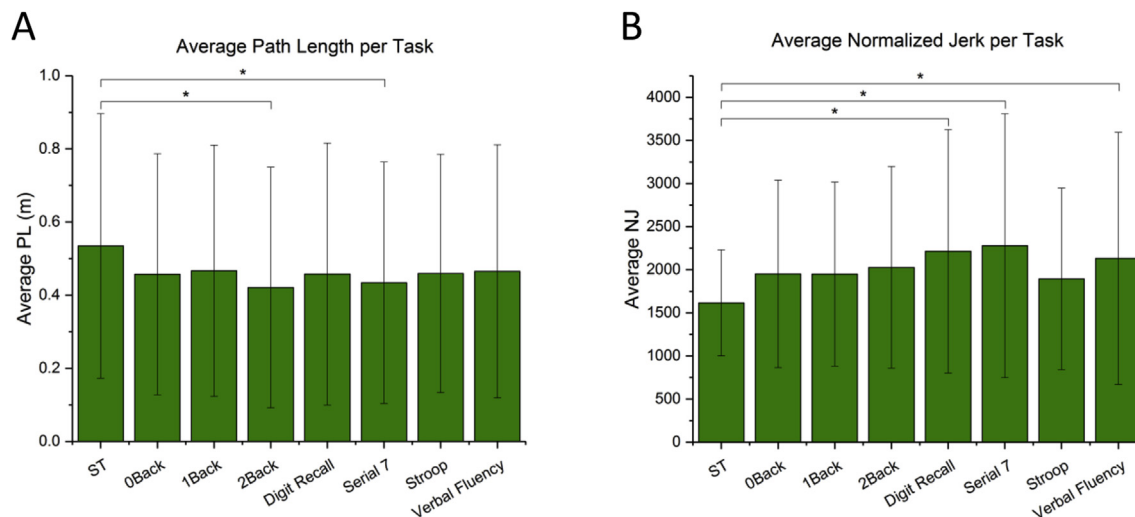
Fig. 3. Average path length (PL) and normalized jerk (NJ). Comparing ST to DT for PL (A) and NJ (B), data collapsed across sides, statistically significant worsening from ST to DT denoted by *, p = .05.

significant differences in NJ were found in both arms. This suggests that control of fluidity of movement in PD employs executive function, and can be disrupted with sufficient cognitive loading.

Postural reflexes are necessary for maintaining dynamic balance during walking, and are disrupted in PD [22]. Increases in variability in gait measures, including arm swing [7], may be indicative of decreases in postural reflex function [22]. Increased gait variability leads to decreases in postural stability during gait, which further leads to increased falls [12]. The greatest increase in cvAST from ST to DT occurred in the serial-7 task (45.26%). Although this did not reach statistical significance, it is similar to the results of a comparable study [7]. Mirelman et al. found a significant increase in variability in arm swing magnitude when moving from ST to DT of 44.74%; differences in sample size likely contribute to the lack of statistical significance [7].

Posture second strategy is commonly seen in DT conditions in individuals with PD, which results in the participant exhibiting greater declines in the physical/motor portion of the DT compared to the cognitive portion, choosing "posture second" in a priority ranking. Unfortunately, this strategy poses increased risk for postural instability [13]. This study demonstrates that the impacts of posture second strategy extends beyond the lower extremity movements required of the gait task, to motor control of the body as a whole. The participants of this study appear to adhere to this DT strategy, with the serial-7, 2-back, digit recall, and verbal fluency tasks resulting in decreases in PL and increases in NJ.

In mostly automatic activities such as walking, executive function supplements as a compensatory control strategy to complete movements [4], yet frontal cortical activity is impaired due to basal ganglia dysfunction in PD [5] resulting in increased gait impairment in cognitive-motor DT conditions. The serial-7 task appears to place sufficient load on executive function (e.g. working memory) to elicit a significant decline in upper extremity function for two arm swing measures, while other tasks resulted in decline for either the PL or NJ measure, or no significant declines at all. The inconsistencies in gait decline across various DT conditions suggests that the cognitive domain assessed taxes executive function, and therefore gait, differently.

There are limitations to this project. The PD population was comprised of mild to moderately affected individuals, and it is unclear if a more severe population would yield different results. Furthermore, patients with deep brain stimulation, a treatment

that complicates DT performance [23], were not included in this study. Further research is needed to evaluate the impact of deep brain stimulation under various stimulation settings on arm swing and cognitive performance under DT conditions. Lastly, while the self-paced treadmill allowed for collection of a greater number of gait cycles than over-ground walking in a motion capture environment, the correlation between the simulated cognitive-motor DT conditions and those experienced in real life scenarios has yet to be determined.

5. Conclusion

Arm swing measured by PL and NJ resulted in declines under DT conditions in a PD population. The cognitive and attentional demands required of the serial-7, 2-back, digit recall and verbal fluency tasks are significant enough to sequester the additional attention that people with PD typically require for functional gait. Future research in this area should focus on how interventions and treatments affect arm swing across various cognitive domains. It may be useful to target cognitive therapies in the areas which demonstrated greatest decline to ascertain if improvements are achievable, and are translatable into daily activities.

Contributors

Elise I. Baron: Design and execution of statistical analysis; writing of the manuscript. Mandy M. Koop: Review of statistical analysis; review of the manuscript. Matthew Streicher: Data collection; methods section of manuscript. Anson Rosenfeldt: Conception and management of research project; subject information section of manuscript. Jay L. Alberts: Conception of research project, writing of the supporting grant, review of the manuscript.

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