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Mobility improves after high intensity aerobic exercise in individuals with Parkinson's disease

Mandy Miller Koop[a], Anson B. Rosenfeldt[a], Jay L. Alberts[a,b,c,*]

[a] Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH, United States of America
[b] Center for Neurological Restoration, Cleveland Clinic, Cleveland, OH, United States of America
[c] Cleveland Clinic Concussion Center, Cleveland Clinic, Cleveland, OH, United States of America

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ABSTRACT

Emerging literature indicates aerobic exercise improves the motor symptoms associated with Parkinson's disease (PD). However, the impact of aerobic exercise on functional locomotor performance has not been evaluated systematically. The aim of this project was to determine the impact of an 8-week high intensity aerobic exercise intervention on Timed Up and Go (TUG) performance in PD. Fifty-nine participants with idiopathic PD completed 24 aerobic exercise sessions over 8 weeks. Two modes of exercise were utilized: forced (FE) and voluntary (VE). A mobile application was used to gather biomechanical data for the characterization of the TUG subtasks: Sit-Stand, Gait, Turning, and Stand-Sit. Participants were assessed in an off medication state at: 1) baseline, prior to any exercise intervention, and 2) after completion of exercise treatment. At baseline, the VE group completed the TUG in 9.41 s, while the FE group completed the TUG significantly faster in 8.0 s. Following the exercise intervention, the VE group decreased TUG time to 8.9 s ($p < .01$). Both exercise groups demonstrated significant improvements in Turning Velocity, time of Gait phase and Stand-Sit duration. Overall mobility in participants with PD was significantly improved after high intensity aerobic exercise training. Improvements in turning and gait speed, and in Stand-Sit times indicate exercise is effective in improving functional aspects of mobility that are often associated with falls and quality of life measures. These results support the use of high intensity aerobic exercise for improvements in functional lower extremity performance in a PD population.

1. Introduction

Parkinson's disease (PD) is a neurodegenerative disease that affects nearly 6.1 million individuals worldwide [1]. The cardinal symptoms include tremor, bradykinesia, rigidity and postural instability. Postural instability can be one of the most disabling symptoms because it predisposes individuals with PD to unexpected falls and is often refractory to pharmacological and surgical interventions.

"Exercise is medicine" is a relatively new term as it applies to the treatment of PD. However, evidence is mounting that high intensity exercise should be part of the medical management of PD. [2–5] Treadmill training has been shown to improve gait velocity, step length, and reduce gait variability in individuals with PD. [6–8] Given the specificity of training principle, improvements in gait variables following treadmill training are not surprising. Notably, there are several reports of stationary cycling protocols improving gait performance (i.e. velocity and cadence), as well as complex mobility as measured by the Timed Up and Go (TUG) [9–11]. Since the TUG requires an individual to perform multiple functional tasks (sit-stand, stand-sit, ambulate in straight line, turn), the positive results provide preliminary evidence that cycling can improve multiple aspects of functional mobility. While this finding is promising in the use of exercise to treat lower extremity dysfunction, total time to complete the TUG does not provide insight into specific aspects of performance that may be most compromised as a result of PD, such as turning and transitioning from standing to sitting. Parsing the TUG and evaluating the performance in distinct motor tasks provides greater resolution for detecting impairments and identifying potential improvements following an exercise intervention.

The parsing of the TUG into its five distinct subtasks has been completed previously using 3-dimensional motion capture systems [12,13] and more recently using wearable inertial monitoring unit (IMU) sensors by our group and others [14,15]. Salarian and colleagues reported that total time was similar between individuals with PD and their healthy peers; however, individuals with PD displayed

* Corresponding author at: Dept. of Biomedical Engineering, Lerner Research Institute Cleveland Clinic, 9500 Euclid Ave., Cleveland, OH 44195, United States of America.
E-mail address: albertj@ccf.org (J.L. Alberts).

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impairments in the multiple subtasks of the TUG (gait, turning, sit-stand) [14]. Ponti and colleagues reported that an analysis of the TUG components was able to discriminate between fallers and non-fallers in healthy older adults; however overall time did not [16]. Both of these studies highlight the importance of segmenting the TUG into phases to provide greater insight into functional status; nevertheless, approaches in both of the aforementioned studies required a multi-IMU based motion capture system, or a multi-step process of collecting, and transforming the raw data into an easily-understood report that could be utilized for clinical recommendations. Due to time and financial constraints, the subtask analysis of the TUG has not been systemically incorporated into research protocols or clinical workflows.

In a recent publication we showed that IMU data from an iPad coupled with a custom built application, the Cleveland Clinic Mobility and Balance Application (CC-MB), could be used to segment the TUG into the subtasks. Analysis of mild-to-moderate PD patients on and off medication detected a significant improvement with medication in total time to complete the TUG. Analysis of the subtasks revealed that much of that difference was due to a 10.4% improvement in turn duration and an 8% improvement in turn velocity in the on-medication state [15]. Importantly, utilizing a mobile platform allows for a low-cost, easy-to-use tool that can generate reports with biomechanical outcome metrics for each of the subtasks of the TUG along with total time.

The Cyclical Lower Extremity Exercise for Parkinson's (CYCLE) trial was conducted to systematically evaluate the effects of a high intensity cycling program on individuals with PD. [17] Improvements in motor performance [5], control of grasping forces [3,5], preserved olfaction [18], and improved connectivity in the subcortical-cortical central nervous system [4,19], indicated that high intensity aerobic exercise performed with the lower extremities resulted in global changes in motor function in PD patients. Collectively, our previous studies provide rationale to systematically evaluate the impact of high intensity aerobic exercise on overall mobility in PD via an instrumented TUG.

The aim of this project was to determine the effects of an 8-week high intensity exercise intervention on overall mobility, including gait and turning function, measured by the TUG in individuals with PD. Based on positive effects of exercise on motor and non-motor performance [5,18,20], it was hypothesized that high intensity aerobic exercise would improve biomechanical measures of mobility.

2. Material and methods

The data presented were gathered from a subset of patients participating in the aerobic intervention from a larger clinical trial (CYCLE trial). The technology for the CC-MB was in development when the trial was initiated. Once available, it was utilized with the remaining patients enrolled in the clinical trial. Details related to the specifics of the exercise protocol have been described previously [17]. Informed consent was gathered from all participants prior to data collection. The consent was approved by the Cleveland Clinic Institutional Review Board. The project was registered with clinicaltrials.gov: registration number NCT01636297.

2.1. Participants

Fifty-nine subjects (32 males) from the CYCLE trial data were tested with CC-MB application and had participated in the exercise intervention. These subjects had a previous diagnosis of idiopathic PD by a neurologist and were recruited from the Cleveland Clinic Center for Neurological Restoration. Demographic characteristics are provided in Table 1. Primary inclusion criteria included: clinical diagnosis of idiopathic PD, age between 30 and 75 years, not currently engaged in formal exercise intervention or clinical study, and Hoehn and Yahr stage I-III in an on-medication state. Primary exclusion criteria included: existing cardiopulmonary disease, history of stroke, dementia, and any medical or musculoskeletal contraindications to exercise. After completion of the initial inclusion/exclusion screen, participants underwent a cardiopulmonary stress test on a standard, upright bicycle to further screen for cardiac abnormalities. Then participants were randomly allocated into either a forced exercise (FE) or voluntary exercise (VE) group via an envelope pull. Both cycling intervention groups participated in the exercise program 3 × /week for 8 weeks for a total of 24 sessions.

Table 1
Participant demographics.

	FE	VE	p-Value
	N = 31	N = 28	
Sex	58% Male	50% Male	0.54
Age (years)	63.23 (8.2)	62.04 (8.3)	0.58
PD Duration (years)	3.35 (3.6)	4.09 (3.7)	0.44
Levodopa Equivalent	410.61 (329.9)	676.61 (1293.9)	0.29
UPDRS III Off Medication	35.97 (9.0)	39.11 (9.9)	0.21
Hohen & Yahr	2.10 (0.4)	2.25 (0.5)	0.24

Values provided as mean (SD) unless otherwise noted.

2.2. Forced exercise (FE) intervention

Participants in the FE group exercised on a stationary recumbent bicycle with a custom engineered motor and control algorithm that augmented cadence by 30% [3,5,21]. It is important to note that although the participants in the FE group cycled at an augmented rate, it was an active, not passive, activity. In order to ensure that the participant was actively contributing to the pedaling motion, the algorithm used to control the assisted-cycle was responsive to pedal rate, the torque exerted on the pedals by the participant, and the torque produced by the motor during exercise. The cadence was set to a rate that was approximately 30% greater than the individual's self-selected pace that was determined during the initial screening. Each exercise session consisted of a 5 min warm-up, 40 min main exercise set, and a 5 minute cool down. To ensure active participation, participants were asked to exercise at 60–80% of their heart rate reserve, calculated using the Karvonen method based on the results of their cardiopulmonary stress test [22]. Heart rate and pedaling cadence were continuously monitored and recorded every 5 min, while rate of perceived exertion was recorded every 10 min by an exercise physiologist.

2.3. Voluntary exercise (VE) intervention

The VE intervention sessions were conducted in an identical frequency, duration, and intensity as the FE sessions. The only difference from the FE group was the mode of exercise. Participants in the VE group exercised on a stationary recumbent bike at a self-selected cadence. Again, subjects were encouraged to exercise at 60–80% of their heart rate reserve and were monitored in an identical manner to the FE group.

2.4. Experimental protocol

Individuals with PD completed the TUG at baseline and at the end of the 8-week treatment (EOT). Both assessments were in the “off medication” state, meaning that participants refrained from taking their antiparkinsonian medication for at least 12 h prior to testing. The Movement Disorder Society – Unified Parkinson's disease Rating Scale (MDS-UPDRS) motor examination [23] was administered by the same blinded rater at both time points.

As part of the TUG testing, an Apple iPad® (Cupertion, CA) mobile device was secured to the back of the subject at sacral height to approximate whole body center of mass [24–28]. In a flat, carpeted hallway, subjects sat on the front edge of an armless chair to begin the

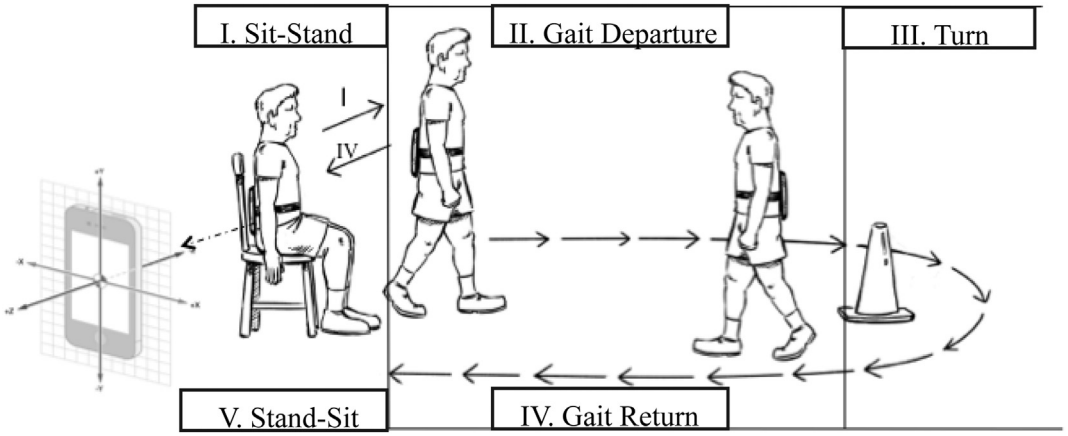

Fig. 1. Timed Up and Go test with defined phases.

trial. Upon hearing the auditory start signal from the CC-MB app, the subject stood up from the chair, walked to a small cone positioned 3 m away, performed a 180-degree turn, walked back to the chair, and turned to return to a seated position (Fig. 1). Each subject completed two trials per assessment.

2.5. Data acquisition and analysis

A custom application for the mobile device platform was created to acquire and store 3D accelerometer (ST Micro LIS331DLH) and 3D gyroscope (ST Micro L3G4200D) data from the embedded sensors in the mobile device during the task [24]. Data from both sensors were sampled at 100 Hz. Device specification and details on data storage have been described previously [24]. Following test completion the administrator extracted the data from the tablet using the CC-MB app, and data were securely transmitted to a HIPPA compliant research database for off-line data analysis in MATLAB (TheMathWorks, Inc.).

The acceleration signal utilized in the analyses of this manuscript was the 'userAcceleration' signal, which is directly exported from the iPad and has been previously described [15]. The exported 'user-Acceleration data' and the gyroscope data measured motion with respect to an internal 3-dimensional, orthogonal, right-handed coordinate system. Although care was taken to position the iPad in the same orientation on all trials, small deviations in positioning the device could lead to erroneous results when data is compared across trials. To avoid this, the 'gravity' acceleration signal, the estimated acceleration due to gravity measured in the device reference frame, was also exported from the iPad. The first 10 samples of the 'gravity' acceleration data from each trial was used to construct an inertial 3-dimensional orthogonal coordinate system where the acceleration due to gravity was only measured in one axis (vertical) via direction cosine matrix calculations [29]. For each trial, the measurements of the iPad sensors were transformed to an inertial coordinate system through the use of the direction cosine matrix which standardized the measurements across patients and trial, and these measurements are what is reported in this study.

Each trial was segmented into the five phases: Sit-Stand, Gait Departure, Turn, Gait Return, and Stand-Sit (Fig. 1) using the linear acceleration and angular velocity in the anterior-posterior (AP), medial-lateral (ML) and vertical (V) directions as previously described [15]. The outcome metrics for this study were a subset of measures that have shown to differentiate between TUG in early stage PD off medications compared to age-matched healthy controls [14,30–32]. Time duration (secs) was calculated for Sit-Stand, Gait Departure and Return, Turning, Stand-Sit, and Total Trial. Turning IMU metrics included average turn velocity (deg/s), root mean square of linear acceleration (RMS) (m/s^2) in AP, ML, and V directions. For gait IMU metrics, gait departure and gait return metrics were overall similar and therefore data was collapse across gait tasks and reported as Gait data for each metric. Root mean square of linear acceleration (RMS) (m/s^2) was calculated in AP, ML, and V directions. The Gait Normalized Jerk Score (NJS) (m) in all 3 directions was calculated using the time duration between each foot contact using the Gait NJS equation in which states:

$$Gait\ NJS = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\frac{(hs_{i+1}-hs_i)^5}{2}}\int_{hs_i}^{hs_{i+1}}(\ddot{a})^2 dt \quad (1)$$

where hs_i represents the time of the ith heel strike and a is the acceleration in (m/s^2).

Extensive details regarding filtering methods, and equations for each kinematic outcome variable have been previously reported [15].

2.6. Statistical analysis

The aim of this project was to determine the effects of an 8-week high intensity exercise intervention on overall mobility. A linear mixed effect model including a random intercept were used to determine the effects of exercise on the TUG outcome measures. The main effect of group (VE, FE), main effect of visit (Baseline Off, EOT), and the group × visit interaction were all examined. Subject number and trial were included as random effects, and alpha = 0.05.

3. Results

3.1. Exercise compliance and characteristics

Exercise compliance data are provided in Table 2. Both groups demonstrated good exercise adherence and cycled at similar exercise parameters. There were no significant differences in compliance variables between groups.

3.2. Effects of exercise on functional mobility

TUG outcome metrics for the VE and FE groups at baseline and EOT

Table 2
Exercise compliance.

	FE	VE	p-Value
	N = 31	N = 28	
Exercise Attendance	90%	96%	0.10
Power (Watts)	40.2 (22.9)	50.1 (25.8)	0.12
Cadence (RPM)	78.7 (10.6)	73.6 (15.6)	0.15
Heart Rate Reserve %	67% (8%)	71% (13%)	0.11

Values presented as mean (SD) unless otherwise noted.

Table 3
Mean (SD) for TUG Functional Mobility and IMU Metrics for VE and FE at Baseline and EOT.

	FE Baseline	FE EOT	VE Baseline	VE EOT	Visit	Group	Visit × Group
	N = 31	N = 31	N = 28	N = 28	p-Value	p-Value	p-Value
Functional Mobility							
Total time (sec)	8.00 (1.55)	7.94 (1.84)	9.41 (2.17)	8.90 (2.19)	0.69	< 0.01*	0.04*
Sit-Stand (sec)	0.79 (0.34)	0.82 (0.30)	0.88 (0.38)	0.83 (0.35)	0.86	0.40	0.32
Gait Departure (sec)	1.98 (0.76)	2.00 (0.73)	2.59 (1.23)	2.42 (1.09)	0.41	0.01*	0.25
Turn (sec)	1.54 (0.28)	1.50 (0.42)	1.69 (0.34)	1.65 (0.38)	0.43	0.03*	0.57
Gait Return (sec)	1.79 (0.42)	1.75 (0.47)	2.18 (0.54)	2.05 (0.58)	0.04*	< 0.01*	0.21
Stand-Sit (sec)	1.90 (0.45)	1.85 (0.58)	2.07 (0.63)	1.93 (0.57)	0.03*	0.98	0.27
Turning-IMU Metrics							
Velocity (deg/s)	92.45 (13.49)	95.03 (17.62)	85.37 (14.50)	88.14 (16.96)	0.04*	0.04*	0.94
RMS-AP (m/s^2)	2.50 (0.94)	2.65 (0.98)	2.14 (0.70)	2.35 (0.87)	0.01*	0.82	0.67
RMS-ML(m/s^2)	2.48 (0.71)	2.58 (0.82)	2.04 (0.39)	2.21 (0.68)	0.01*	0.007*	0.51
RMS -V (m/s^2)	1.86 (0.59)	1.85 (0.73)	1.62 (0.46)	1.71 (0.47)	0.88	0.06	0.29
Gait – IMU Metrics							
RMS-AP (m/s^2)	2.81 (1.03)	2.86 (1.04)	2.52 (0.91)	2.68 (0.92)	0.17	0.27	0.47
RMS-ML (m/s^2)	2.34 (0.90)	2.46 (0.92)	1.85 (0.44)	2.05 (0.75)	< 0.01*	0.01*	0.40
RMS-V (m/s^2)	2.35 (0.65)	2.42 (0.78)	2.03 (0.45)	2.15 (0.44)	0.03*	0.03*	0.65
NJS-AP (m)	6.61 (3.20)	7.45 (3.70)	6.31 (2.91)	7.06 (3.47)	< 0.01*	0.61	0.87
NJS-ML (m)	5.65 (2.84)	6.67 (3.67)	5.07 (2.31)	5.67 (2.82)	< 0.01*	0.22	0.35
NJS-V (m)	4.43 (1.92)	5.24 (2.71)	4.25 (1.73)	4.78 (2.03)	< 0.01*	0.47	0.46

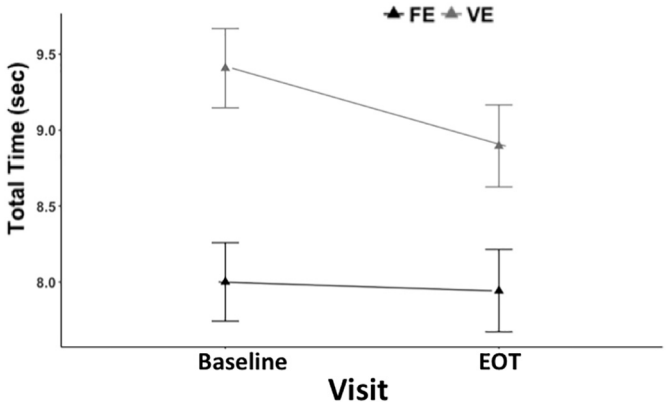

Fig. 2. Effects of exercise on Total Time. VE was significantly faster in completing the TUG at after the exercise intervention ($p < .01$), whereas the FE group was not (significant group × visit effect ($p = .035$)). Baseline times for FE group were significantly faster compared to VE ($p = .005$).

are shown in Table 3. For total trial time there was a significant group × visit interaction ($p = .035$) indicating that the effect of exercise on total trial time was different across the groups (Fig. 2). Post-hoc testing revealed the VE group completed the TUG task significantly faster at EOT (8.90 s) compared to baseline (9.41 s, $p < .01$), whereas the FE group demonstrated no change in performance time between visits ($p = .9$). However, baseline total time was significantly faster for the FE group compared to the VE ($p = .005$), and EOT times for FE were also faster at compared to VE, but not significantly ($p = .054$).

Analyzing the time durations of the phases of the TUG provided greater resolution into the specific improvements in lower extremity performance. There was no significant group × visit interaction on any subtask outcome metric ($p > .05$, all measures). However, there was a significant main effect of visit for Gait Return time ($p = .04$) and Stand-Sit time ($p = .03$), indicating that exercise significantly improved timing in these subtasks at EOT compared to baseline for both groups (Table 3). In addition, there was as a significant main effect of group for Gait Departure ($p = .01$) and Gait Return ($p = .04$) times, and Turn duration ($p < .01$), with post hoc tests indicating that for these subtasks the FE group was significantly faster across visits compared to the VE group (Table 3) and (Fig. 3).

3.3. Kinematics of turning

Turning velocity was significantly improved across both groups at EOT compared to baseline as evidenced by a significant main effect of visit ($p = .04$) (Table 3). Additionally there was a main effect of group on turning velocity ($p = .04$) with post hoc tests revealing that the FE group had significantly greater velocity than VE ($p < .05$), and no significant interaction $p = .94$ (Table 3). Analysis of turning kinematics revealed significant improvements in acceleration in the ML and AP axes across both groups at EOT compared to baseline; with a significant main effect of visit $p = .01$ for both (Table 3). Additionally, there was a main effect of group for RMS ML ($p = .007$) and post hoc tests revealed that the FE group was significantly greater than VE, with no significant interaction $p = .51$ (Table 3). There was no significant main effect of group, visit or their interaction on the RMS of acceleration in the V direction ($p > .05$) (Table 3) and (Fig. 3).

3.4. Kinematics of gait

Measures of acceleration improved for both FE and VE in all axes as measured by NJS, evident by a significant main effect of visit (Table 3), indicating that gait was more dynamic in all direction of movement following the exercise intervention. Specifically, ML direction showed the greatest improvement, ($p < .01$), followed by vertical ($p < .01$) and AP ($p < .01$) (Table 3). In addition, there was a main effect of group on the RMS of acceleration in the ML ($p = .01$) and V ($p = .03$) directions, indicating that the FE group had a significantly larger amplitude of acceleration compared to the VE group (Table 3).

4. Discussion

An 8-week high intensity aerobic exercise program in individuals with PD improved turning, gait metrics and coordination of sequential movements during transfers as measured by an instrumented version of the TUG. The VE group experienced an improvement in total time (~0.5 s) following exercise, while those in the FE group did not demonstrate a decrease in total time. Notably, baseline performance of the FE group indicated relatively high gait function with a TUG total time of eight seconds, which is comparable to their age-matched healthy peers [33]. It is likely the FE group experienced a ceiling effect with regard to total time to perform the TUG.

Improvements in total time to complete the TUG following a cycling

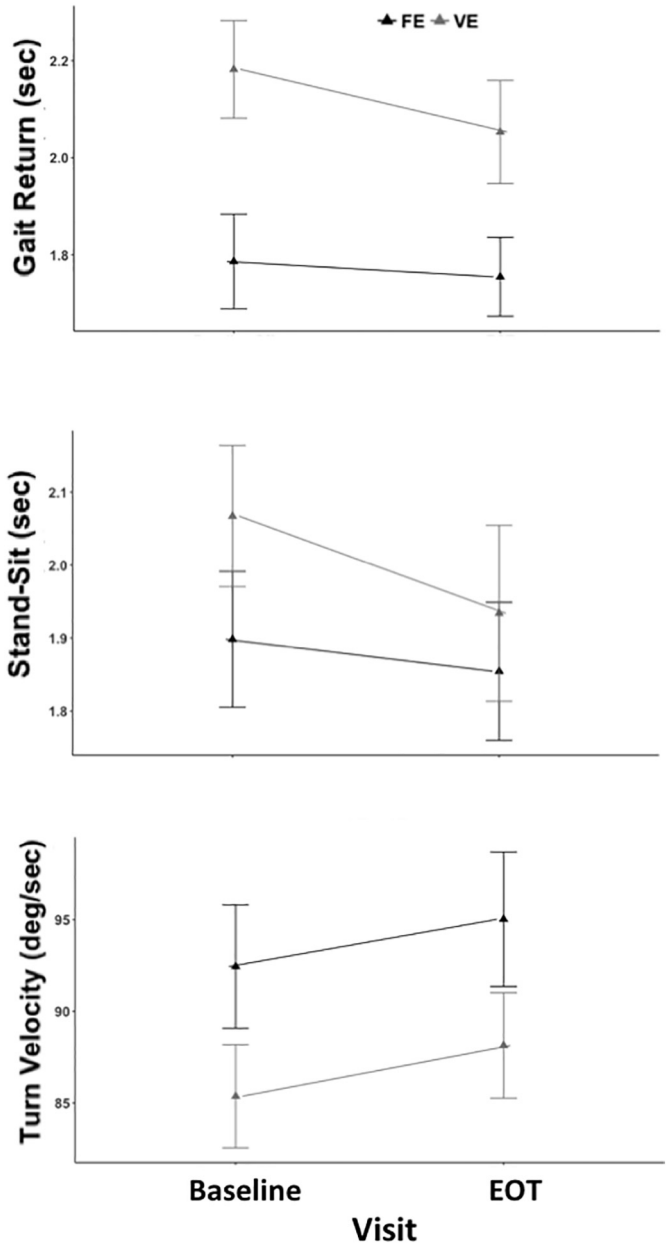

Fig. 3. Effects of exercise on subtasks of TUG. Gait Return time, Stand-Sit time, and Turn Velocity were significantly faster for both FE and VE groups after the exercise intervention (main effect of Visit- $p < .05$ for all, with no significant interaction- $p > .05$ for all). Turn Velocity and Gait Return times were overall faster in the FE group compared to VE (main effect of Group- $p < .05$ for both).

intervention have been reported previously [9–11]. The current approach to separating and analyzing the distinct subtasks provided greater insight into potential mechanisms underlying improvements in functional mobility following exercise. Exercise improved metrics in each of the following phases for both the VE and FE group: Stand-Sit, Gait and Turning Velocity. Specifically the rate of acceleration in gait, as measured by NJS, was improved in all axes leading to an overall improvement in Gait Return time for both groups. In addition, there were increases in the average amplitude of acceleration during turning, measured by RMS values, in the ML and V axes which resulted in a faster turning velocity for both group. Precise characterization of the individual phases of the TUG revealed that the FE group was significantly faster in most phases compared to the VE group, providing further evidence that the FE group experienced a ceiling effect with this clinical test at baseline.

Collectively, exercise resulted in improvements in multiple facets of mobility – transfers (e.g. stand-sit), gait and turning. While all three aspects of mobility require dynamic postural control, each requires a very different aspects of motor planning and execution. Turning requires greater asymmetrical limb coordination, weight shifting, and step width modulating, compared to straight line walking [34,35]. Evaluation of turning performance has been shown to be critical for identifying postural instabilities associated with PD that could result in falling. Notably, falls during turning result in an eight-fold increase in hip fracture compared to falls that occur during walking in a straight line [36]. The current data indicate that a high intensity cycling intervention may improve the motor control processes responsible for complex motor activities, such as turning.

The demonstration that exercise impacts multiple aspects of functional mobility and subsequently impacts different motor control processes provides additional support for the concept that aerobic exercise can, in PD patients, enhance central nervous function. Global changes in lower extremity motor control are consistent with our previous findings that high intensity aerobic exercise facilitates a change in motor control processes from feedback to feed-forward in the control and coordination of grasping forces during a bimanual object manipulation task [5]. It is proposed a similar improvement in motor control processes is underlying improvement in functional mobility. The successful performance of a turn requires the integration of visual, proprioceptive and vestibular information. We have previously hypothesized that high intensity exercise via a stationary bicycle may be increasing the quality and quantity of afferent information sent to cortical and subcortical areas [3]. It is plausible that an enhancement in afferent information during exercise may facilitate the processing and integration of sensory information which may underlie improvements in aspects of performance.

The use of technology with the TUG provides insight into a potential mechanism of improvement seen in this study. Bradykinesia directly affects gait and turning in individuals with PD, resulting in short, narrow steps, a flexed, rigid trunk, and poverty of movement in the upper extremities. Increases in NJS scores, or rate of acceleration during gait indicate that individuals in this study experienced a decrease in bradykinesia during gait. The RMS of acceleration has been described as the average positive amplitude of acceleration for a given movement [37]. Improvements in the RMS in turning indicate a global increase in amplitude, which again is indicative of decreased bradykinesia. The precise mechanism underlying motor improvements in this patient population is unknown. Based on animal studies, there is likely an elevation of neurotrophic factors that facilitate neural functioning and may facilitate angiogenesis [38,39]. Imaging data indicate that high intensity exercise results in greater levels of connectivity between sub-cortical and cortical structures [4,21] and similar patterns of activation in exercise and anti-parkinsonian medication [19]. Additional studies focusing on the precise mechanism will be important to further refine an exercise prescription in which specific types and intensities could be prescribed for a given motor or non-motor phenotype.

Our results add to a growing body of literature that exercise intensity is more important than mode in mitigating motor symptoms of PD, as the FE and VE groups exercised at similar exercise intensities as measured by cadence, HRR, and power. Low-dose physical and occupational therapy did not improve outcomes in individuals with mild to moderate PD [40]; however, a non-futility study supported that high intensity treadmill training is feasible, safe, and warrants further investigation into efficacy [2]. Additionally, Arcolin and colleagues reported that treadmill and cycling training at similar intensities resulted in comparable improvements in gait, mobility, and balance outcomes [41]. Collectively, these results indicate that high intensity exercise can be delivered via multiple modes to result in global improvements in function for individuals with PD.

Previously, multiple sensor systems have been used to parse components of the TUG, through the use of motion capture systems,

multiple accelerometers and gyroscopes, and/or with video [14,30,31,42,43]. These methods prove to be time-consuming, costly, and require highly technical skilled workers to administer and analyze data. The advantages of the CC-MB application is its utilization of a commercially available device (iPad) that is affordable and widely available. The assessment module can be administered by non-medical personnel and the data can be integrated into the electronic health record. The CC-MB has the potential to enhance the continuity of care and communication between neurologists and physical and occupational therapists through the sharing of objective data through a standardized evaluation such as the TUG in which objective measures are used to characterize performance. Standardized evaluations may accelerate referral to rehabilitation services, allow physicians to understand the value of therapeutic intervention, and facilitate multidisciplinary decision-making regarding treatment approaches.

Areas of future research include expanding a high intensity aerobic exercise protocol to individuals with moderate to severe disease. The individuals in this study were mildly impaired and therefore provided the necessary dynamic changes in the data for identification and segmentation of the TUG into the individual subcomponents for analysis. It is unknown if the sensor system in the iPad could detect behaviors in individuals with PD with more severe disease symptoms, including a shuffling gait or very slow turning behavior. Furthermore, although no participant complained of the iPad hindering their movements, it is unclear how the addition of the iPad to the lower back affected participant performance. Although care was taken to mitigate baseline differences between the two groups by using an envelope pull to randomly allocate subjects to the FE and VE groups, baseline differences were still present. Future studies will include larger number of participants and/or a permuted block process to allocate subjects to the different groups to further help reduce baseline difference [44]. A strength of this study was the diligent monitoring of exercise variables, providing a detailed description of intensity in the exercise cohort. Further work is merited to determine a precise exercise prescription which optimizes improvements in PD symptoms, and to determine the clinical meaningfulness of the changes detected in this study. This study provides further evidence that aerobic exercise may be an effective adjunctive therapy in the treatment of PD symptoms. As rehabilitation specialists search for effective, disease-specific interventions to be implemented in a clinical and community setting, high intensity aerobic exercise delivered on a stationary bicycle appears to be a viable option.

5. Conclusions

Overall functional mobility of PD patients was enhanced following high intensity aerobic exercise training. Specifically, complex aspects of functional mobility (e.g. turning and stand-to-sit) improved significantly following the intervention. Enhanced performance of complex lower extremity function suggest exercise may be transitioning motor control processes from feedback to greater utilization of feedforward strategy. The development of a mobile application that is capable of parsing the TUG into its movement components has the potential to transform the care of PD patients by taking a standardized set of biomechanical based measures from the laboratory and bringing them to the clinical and rehabilitation settings.

Conflicts of interest

JLA has authored intellectual property related to the motor control algorithm for the stationary exercise bicycle. The remaining authors declare no conflicts of interest.

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Portions of the results have been presented as poster and platform presentations at the Society for Neuroscience Annual Meeting 2017 and the American Physical Therapy Association Combined Sections Meeting 2018.

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