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ABSTRACT

Postural instability is a primary symptom of advanced Parkinson’s disease (PD). Falling, loss of mobility, and restriction of activity due to postural instability have a major influence on the health and quality of life of PD patients. Presently, clinical measurement of postural stability in PD is crude. Patient recovery to a sudden, backward pull of the shoulders by the physician (the retropulsion test) typically serves as an index of postural instability. The retropulsion test is subjective and there are presently no standards to govern its administration. In addition to the lack of sophistication in clinical measurement, little is known about factors that interact with postural instability to threaten balance for people with PD. The purpose of the present study was to employ static posturography (objective, quantitative measurements of naturally occurring postural sway obtained from a computerized biomechanics system called a force platform) to determine how visual perception and the attentional demands of a visuo-spatial cognitive task affected postural stability in PD. The results of the study indicated that the postural sway of PD patients in H-Y stage 3 (Hoehn & Yahr, 1967; H-Y stage 3 is a fairly advanced stage of PD at which balance and gait problems appear) was more variable than that of elderly, healthy controls. In addition, a time series technique called recurrence quantification analysis revealed that the spatiotemporal profile of postural sway for PD patients reflected greater recurrence (auto-correlation), determinism, mathematical stability, and complexity in the anterior-posterior sway direction. Recurrence was also higher (in the medial-lateral sway direction) with vision than without vision. No effects of the cognitive task were found. The results suggest that the
novel combination of static posturography and RQA reliably differentiated PD patients from control participants.
### TABLE OF CONTENTS

**TABLE CAPTIONS** ....................................................................................................... ii  
**FIGURE CAPTIONS** ..................................................................................................... iii

**CHAPTER 1** ................................................................................................................... 2

**Introduction** ................................................................................................................. 2

- *Postural stability in Parkinson’s disease* ............................................................. 3
- *The relation between postural control and visual perception* .......................... 6
- *Posture and performance of a cognitive task as competitors for central resources* ..... 7
- *Preview of the present study* ................................................................................. 8
- *Predictions* .............................................................................................................. 9

**CHAPTER 2** ................................................................................................................. 12

**Method** ...................................................................................................................... 12

- *Participants* ........................................................................................................... 12
- *Apparatus* .............................................................................................................. 14
- *Procedure* .............................................................................................................. 14
- *Data Analysis and Reduction* ............................................................................. 16

**CHAPTER 3** ................................................................................................................. 19

**Results** ....................................................................................................................... 19

- *Time Series Plots and Recurrence Plots* ............................................................. 19
- *Postural Stability* .................................................................................................. 19
- *Spatiotemporal Profile* ......................................................................................... 20
- *Cognitive Task Performance* .............................................................................. 21

**CHAPTER 4** ................................................................................................................. 22

**General Discussion** .................................................................................................... 22

- *Spatiotemporal profile of the COP* ..................................................................... 23
- *Absence of a cognitive task effect* ...................................................................... 26
- *Implications for Parkinson’s Disease* ................................................................. 27
- *Future directions* .................................................................................................. 30
- *Conclusion* ............................................................................................................ 31

**REFERENCES** ............................................................................................................. 33

**APPENDIX A: Recurrence Quantification Analysis** ................................................... 47

**FOOTNOTE** ................................................................................................................. 55

**TABLES** ...................................................................................................................... 56

**FIGURES** ..................................................................................................................... 58
TABLE CAPTIONS

Table 1: Patient Summary (n = 6) .......................................................... 56

Table 2: Medication Summary (n = 6) ..................................................... 57
FIGURE CAPTIONS

Figure 1. Example of cognitive task stimulus. ..............................................................58

Figure 2. Apparatus and an example of the cognitive task procedure.......................................59

Figure 3. Apparatus and an example of the no cognitive task procedure. .................................60

Figure 4. A typical COP time series for PD and control participants. ........................................61

Figure 5. A typical recurrence plot for PD and control participants...........................................62

Figure 6. COP standard deviation group effect in AP direction..................................................63

Figure 7. COP standard deviation group effect in ML direction..................................................64

Figure 8. COP path length group effect....................................................................................65

Figure 9. % recurrence group effect in AP direction.................................................................66

Figure 10. % determinism group effect in AP direction.............................................................67

Figure 11. Mathematical stability (maxline) group effect in AP direction...................................68

Figure 12. Complexity (entropy) group effect in AP direction..................................................69

Figure 13. % recurrence vision effect in ML direction...............................................................70

Figure 14. A recurrence plot for a randomly shuffled time series. ..........................................71
CHAPTER 1
Introduction

Posture refers jointly to the mutual relationships of the body segments, the global, vertical orientation of the body in the gravitational field, and the orientation of the body to a surface of support (Blaszczyk & Klonowski, 2001). Postural control—the maintenance of upright posture—typically involves the use of most of the body’s major muscle groups; the visual, haptic, and vestibular systems; and sometimes the auditory system. Postural control is essentially a matter of achieving postural stability—the body’s center of mass must be kept within critical boundaries of space defining the body positions that can be maintained without changing the base of support (i.e., the position of the feet; Shumway-Cook & Woollacott, 1995). Postural control can be conceptualized as the adaptive control of the body’s position in space for the purpose of postural stability.

Even though standing seems like a simple behavior, postural control is a substantial perceptual-motor challenge. When a person stands, even in the absence of other activities, the center of mass fluctuates continuously. Standing is characterized by slight, irregular, and continuous movements of the body, termed postural sway (Blaszczyk & Klonowski, 2001). Postural sway results from factors including noisy neuromuscular output, internal perturbations (e.g., breathing), and the mechanical instability of the upright, multi-segmented body (Riley, 2001). Even though postural sway typically consists of small amplitude motion (usually in the range of millimeters to a few centimeters), it can be a threat to balance and thus presents a challenge for the moment-to-moment control of posture (Riley, 2001). Postural control requires a keen
awareness of the body’s orientation to the surrounding environment and precise neuromuscular control in order to overcome perturbations that may arise internally (e.g., postural sway, or moving one’s arm) or externally (e.g., a movement of the support surface).

**Postural stability in Parkinson’s disease**

Parkinson's disease (PD) is a neurological movement disorder associated with bradykinesia (generalized slowness of movements), tremor, rigidity (stiffness of limbs), and postural instability. PD affects up to 1.5 million Americans. Although 15% of patients are diagnosed before age 50, PD is generally considered a disease which targets older adults. PD affects one of every 100 persons over the age of 60. Because of improvements in public health and healthier lifestyle choices, many people now live well into their eighties. Thus, the incidence of PD continues to increase (National Parkinson’s Foundation).

PD is a progressive disorder that results from a degeneration of the substantia nigra (SN), a midbrain structure which forms part of the basal ganglia and is involved in movement control. Cells in the SN interact with other movement control centers by secreting the neurotransmitter dopamine. When the SN cells die, dopamine production declines. Loss of dopamine is associated with erratic neural activity, and as a result CNS movement control centers become unregulated. Most of the movement-related symptoms of PD are associated with degeneration of the SN and the subsequent decline of dopamine. The cause of SN degeneration in the great majority of patients is unknown. Most researchers suspect that the cause of PD is a combination of genetic susceptibility, oxidative stress, accelerated aging, and environmental exposure, and that the genetic and
environmental contributions will vary among different people (National Parkinson’s Foundation).

Chronic postural instability (a degradation of postural stability) is the critical feature differentiating Hoehn and Yahr (H-Y) stage 2 from stage 3 in PD mobility classification (Hoehn & Yahr, 1967). PD patients exhibit an inability to adequately recover postural stability in response to a perturbation, which may be associated with the use of maladaptive muscle coactivation strategies (Shumway-Cook & Woollacott, 1995). PD patients also experience a disruption in anticipatory postural activity, which means that even if they are able to anticipate an impending threat to balance they are unable to implement an appropriate postural control action to prevent the threat from inducing postural instability (Rogers, 1990, 1991). Patients with PD often manifest abnormalities in the latency and amplitude of postural reflexes observed by researchers using dynamic posturography techniques, like rotation of the support surface (toe-up and toe-down perturbations) or movement of the support surface in response to the participant’s sway pattern (i.e., sway-referencing; Beckley, Bloem, & Remler, 1993; Bloem, Beckley, Remler, Roos, & van Dijk, 1995; Bronte-Stewart, Minn, Rodrigues, Buckley, & Nashner, 2002; Horak, Nutt, & Nashner, 1992; Melnick, Dowling, Aminoff, & Barbaro, 1999).

Other studies employing static posturography (quantification of postural sway during “quiet” stance, with no perturbations imposed) indicate that PD participants generally exhibit larger overall amounts of postural instability than age-matched controls or elderly, healthy individuals (Contin, Riva, Baruzzi, Albani, Macri, & Martinelli, 1996; Diener, Dichgans, Bacher, & Gompf, 1984; Rocchi, Chiari, & Horak, 2002; see Schieppati, Hugon, Grasso, Nardone, & Galante, 1994, for a report of greater postural...
instability for PD patients according to one measure of sway, but less instability according to another measure). Taken together, the perturbation and quiet stance studies indicate that PD patients show a general decline in postural stability, but some researchers have cautioned that these findings could indicate in part a change in postural control strategies rather than simply a decline in postural control (Bloem, Visser, & Carpenter, 2001; Schiepatti, & Nardone, 1991; Schiepatti et al., 1994).

Currently, the status of clinical measurement of postural stability in PD is crude. Physicians usually diagnose postural instability using the retropulsion test (how well a patient responds to a sudden backward pull). The retropulsion test is fundamentally subjective because it relies on a physician’s judgment of the patient’s response, and because the pull will vary from physician to physician and test to test. There is also a lack of consensus about how to administer the test (Bloem, Beckley, van Hilten, & Roos, 1998). Variations in patient height and mass introduce additional complications for administering the test, since the effects on the patient of a pull of a given magnitude will depend upon those variables. Furthermore, because few studies have used standardized posturographic techniques in order to control for clinical characteristics and drug schedules of patients, the research reports of objective posture assessment have been contradictory (Contín et al., 1996).

In addition to the lack of sophistication in clinical measurement of postural stability, little is known about factors that interact with instability to threaten balance for people with PD. Since people rarely stand in the absence of other activity—whether that activity is overt motor activity or covert cognitive activity—it is important to understand interactions between postural control and other behaviors (Balasubramaniam, Riley, &
Postural control to other behaviors may be particularly relevant in PD, first of all because PD patients appear to be unable to modify movement patterns in response to changing task demands (Shumway-Cook & Woollacott, 1995), and second because PD patients seem less able to adaptively prioritize the execution of simultaneous behaviors in a way that preserves postural stability (Bloem et al., 2001).

Postural instability associated with PD may ultimately result in loss of independence, injury due to falls, and a decrease in perceived quality of life. Therefore, there may be important functional implications for accurate, early detection of postural instability and for understanding the conditions of daily life that intensify the instability. Further, through the study of cases in which balance is impaired, our understanding of normal balance function will be advanced. Those factors motivated the present study.

The relation between postural control and visual perception

The importance of vision to postural control is well-documented (Dornan, Fernie, & Holliday, 1978; Edwards, 1946; Horak, Shupert, & Mirka, 1989; Nashner, 1989; Paulus, Straube, Krafczyk, & Brandt, 1984; Witkin & Wapner, 1950; Woollacott, Shumway-Cook, & Nashner, 1986). Some researchers have argued that the visual system is the dominant source of information for control of posture (Dietz, Horstmann, & Berger, 1989; Grigg, 1994; Nashner & McCollum, 1985). Postural stability is typically degraded in the absence of vision and is enhanced by the availability of vision (Lee,
During unperturbed stance normal participants are able to maintain balance in the absence of vision, but postural sway may be magnified by a factor of two (Dichgans & Brandt, 1978). The increase in postural sway seen in the absence of vision is generally attributed to a greater visual sensitivity to spatial variables (such as body orientation) relative to proprioceptive or vestibular sensitivity to those variables (Easton, Greene, DiZio, & Lackner, 1998).

**Posture and performance of a cognitive task as competitors for central resources**

Previous research on the effect of cognitive tasks on postural sway is consistent with the emerging view that postural control is not a reflexive and automatic behavior (Woollacott & Shumway-Cook, 2002). Woollacott and Shumway-Cook proposed that assessment methods using dual-task methodologies (engaging in a concurrent cognitive task while controlling posture) are helpful in revealing the effect of disease on the ability to allocate attention to postural control. Since attentional capacities are presumably limited (Broadbent, 1954, 1958; Kahneman, 1973; Posner, 1978; Shiffrin & Schneider, 1977; Wickens, 1984), competition for cognitive resources during dual-tasking might be expected to degrade postural control. This position has been supported by a large body of research (e.g., Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1996; Marsh & Geel, 2000; Maylor, Allison, & Wing, 2001; Morris, Iansek, Smithson, & Huxham, 2000; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Simoneau, Teasdale, Bourdin, Bard, Fleury, & Nougier, 1999; Stelmach, Zelaznik, & Lowe, 1990; Teasdale, Bard, La Rue, & Fleury, 1993; Teasdale & Simoneau, 2001). However, other studies on the relation between postural control and cognitive demand
have produced inconsistent and divergent results that have not always supported that position (see Riley, Baker, & Schmit, in press). Whereas the research cited above indicated that performing a cognitive task when standing is associated with a decrease in postural stability, other studies have indicated that performing a cognitive task when standing is associated with an *increase* in postural stability (e.g., Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Dault, Frank, & Allard, 2001a; Hunter & Hoffman, 2001; Vuillerme, Nougier, & Teasdale, 2000). Other studies have indicated that both increases and decreases in stability accompany concurrent cognitive task performance, depending upon the measure of postural sway employed or upon participant factors such as age (Dault, Geurts, Mulder & Duysens, 2001b; Maylor & Wing, 1996). Those inconsistencies may be due, in part, to confounds or questionable procedures (vocal articulation, motor responses, visual fixation) or the use of coarsely grained statistical descriptors of postural sway (see Dault, Yardley, & Frank, 2003; Riley et al., in press; Yardley, Gardner, Leadbetter, & Lavie, 1999).

**Preview of the present study**

The present study employed static posturography (objective, quantitative measurements of naturally occurring postural sway obtained from a computerized biomechanics system called a force platform) to determine how visual perception and the attentional demands of a concurrent cognitive task affect postural stability in PD. Postural sway measurements were obtained from H-Y Stage 3 PD patients and from age-matched, healthy controls under eyes-open and eyes-closed conditions when participants either engaged in or did not engage in a visuo-spatial cognitive task. Postural sway was operationalized as the center of pressure (COP), which is a measure of the displacement...
of the resultant ground reaction force vector on the force platform, which is equal to the weighted average of the points of application of all vertical forces acting on the force platform (Hamill & Knutzen, 1995). Because the COP reflects characteristics of the center of mass excursions and exhibits properties of active signals used in the control of posture (Blaszczyk, Piorko, Lowe, & Hansen, 1994; Maki, 1986; Prieto, Myklebust, & Myklebust, 1993; Winter, 1995), it provides information about the quality of postural stability. The effects of PD and of concurrent cognitive tasks on postural stability were determined using standard statistical measures of postural stability. Information about the time-evolving patterns and properties of sway were ascertained from an analytical technique called recurrence quantification analysis (RQA; Riley, Balasubramaniam, & Turvey, 1999). Postural sway is a window into normal postural control mechanisms and processes (Riley, 2001). Thus, a change in sway patterns (operationalized by RQA, see Appendix A, see also Webber & Zbilut, 1994, 1998) due to pathology should provide insight into the impact of damage to specific neural pathways on postural control (Collins, De Luca, Burrows, & Lipsitz, 1995; Lauk, Chow, Lipsitz, Mitchell, & Collins, 1999).

**Predictions**

Postural sway has been shown to increase when vision is removed (e.g., Paulus et al., 1984). Riley et al. (1999) also demonstrated (using RQA) a decrease in randomness of postural sway in eyes-closed conditions for healthy, young participants. Those effects of vision were expected to be replicated in the present study and, moreover, were expected to be pronounced in PD patients, who show an increased reliance on visual information in order to control stance (Bronstein et al., 1990).
Due to the previously noted procedural limitations and confounds that characterize much of the existing research on the relation between postural control and concurrent cognitive performance, and based on the results of Andersson et al. (2002), Dault et al. (2001a), Hunter & Hoffman (2001), Riley et al. (in press), and Vuillerme et al. (2000), a decrease in postural sway during dual-task conditions was expected for the control participants. The logic behind this prediction is that when attention must be directed toward a concurrent cognitive task, postural control is released from attentional focus and allowed to work in a more automatic and efficient manner (Hunter & Hoffman, 2001; McNevin & Wulf, 2002; Vuillerme et al., 2000). Since PD patients seem highly susceptible to dual-task interference (Bloem et al., 2001; Shumway-Cook & Woollacott, 1995), the cognitive task was expected to have an opposite effect—an increase in postural sway—for the PD group.

Participants with PD were expected to exhibit a greater amount of postural sway and more variable COP time series than elderly, healthy control participants. This prediction is consistent with previous research on postural sway and PD that showed greater postural sway for PD patients (Contin et al., 1996; Rocchi et al., 2002; Schieppati, et al., 1994).

Postural sway in young, healthy participants exhibits a complex, irregular, variable, and nonstationary profile in the time domain (Riley et al., 1999). Variability of that sort has been shown to be characteristic of the dynamics of normal, healthy physiological process, whereas time series of pathological physiological processes are characterized by stereotypical regularity and a loss of complexity (Goldberger, 1997). Those properties of COP time series can be quantified using RQA. I hypothesized that
PD would be associated with spatiotemporal dynamics that are more regular (higher percent determinism, higher percent recurrence, and lower entropy) but less stable (lower maxline) than sway from elderly, healthy controls (those measures are defined in a later section).

Postural control under normal conditions is an intricate perception-action skill. Any additional constraints imposed on postural control require even greater levels of skill and precision in the control of posture. Thus, differences between healthy controls and PD patients are likely to be enhanced when increasing demands are placed on postural control. The disparity in postural instability between controls and PD patients was expected to increase as experimental conditions became progressively more difficult (i.e., eyes open/no cognitive task vs. eyes closed/cognitive task). Confirmation of that hypothesis would be in accordance with the possibility that PD renders postural control less flexible or adaptive, in the sense that restrictive postural motions may leave the patient’s postural control system less capable of preparing for responses to postural perturbations (Melnick et al., 1999).
CHAPTER 2

Method

Participants

Postural stability was measured in six PD patients (mean age = 70.83 years, SD = 15.89 years, range = 43 years; 2M, 4F) who were receiving neurological services for treatment of PD from physicians in the Department of Neurology at University Hospital in Cincinnati. The patients who participated in the present study were recruited from a larger pool of patients diagnosed by University Hospital neurologists as having progressed to H-Y Stage 3 (Hoehn & Yahr, 1967), the stage of PD at which impairment of walking or standing and onset of postural instability occurs. Earlier stages of PD are differentiated by the symmetry of other PD symptoms (not instability) and later stages of PD are characterized by loss of independence and patient immobility. Since the focus of this study was postural stability, and not on symptom symmetry or severe impairment of mobility, I chose to examine patients at H-Y Stage 3. Postural stability measures obtained from patients were compared to stability measures taken from elderly, healthy controls (mean age = 70.17 years, SD = 4.71 years, range = 13.00 years; 2M, 4F). Control participants with a history of diabetes, arthritis or other illnesses affecting balance, a recent injury, vestibular disorder, dizziness, a history of falls, heavy use of alcohol or other drugs, or chronic back pain were excluded from the study. PD patients were asked to report their medication regimen and to participate in the study during an “on”-phase of the medication cycle. Additional patient information collected from physicians during participant recruitment included disease duration, symptoms of bradykinesia and dyskinesia, rigidity and rest tremor during examination, patient report
of on-off fluctuations in medication cycles, and observations of freezing gait. Physician-observed postural instability was also recorded. Clinical assessment of postural instability in the Department of Neurology was based on a patient’s ability to counter retropulsion (sustained backward stepping) following a perturbation (physician-induced backward thrust of the patient’s upper body). Patient characteristics and medications for the six PD participants included in the study are summarized in Tables 1 and 2.

All PD patients in this study were prescribed dopaminergic therapies, including variations of Sinemet, Comtan, and Amantadine. The primary side effects of levodopa (introduced by several of these medications) include nausea, vomiting, hallucinations, and confusion (Foltynie, Lewis, & Barker, 2002). Because the effect of cognitive demand on postural stability was explored in this study, it was important to conclude that patients’ medications or other aspects of PD (such as dementia) did not induce excessive confusion or cognitive impairment. A criterion level for cognitive functioning was established using the Folstein Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975). This examination was administered to all participants (PD and control) prior to postural stability testing. The MMSE is a brief, quantitative measure of cognitive status in adults. The MMSE assesses orientation, registration, attention and calculation, recall, and language. It has been used to screen for cognitive impairment and demonstrates validity and reliability in psychiatric, neurologic, geriatric, and other medical populations. Participants were excluded from testing if MMSE total scores were lower than 25 (maximum total score is 30). All individuals screened for participation in the study met this criterion. All participants signed a written informed consent document. This study was approved by the University of Cincinnati IRB.
Apparatus

Postural stability data were obtained in this study using a Bertec 4060-NC force platform and Bertec AM-6701 charge amplifier (Bertec Corporation, Columbus, OH). The Bertec force platform is a six-component load transducer that measures the three orthogonal components of a resultant force acting on the platform and the three components of the generated moment in the same orthogonal coordinate system. Data were sampled at 100 Hz and stored on a Pentium-based PC. Datapac 2000 software (Run Technologies, Inc., Mission Viejo, CA) was used for data acquisition and reduction. This software calculated the COP from the force and moment signals measured by the force platform and then computed standard statistical descriptors of the COP (described below).

During data collection, the 12 participants (6 PD and 6 elderly, healthy controls) wore a vest-style, full-body safety harness. A D-ring on the back of the harness was connected to a ceiling anchor via a three foot lanyard for purposes of fall-arrest (no participants actually fell or lost balance during testing). Participants stood 1.23 m from a 36.8 × 25.4 cm flat-panel monitor (mounted on an adjustable stand at each participant’s eye height), which was used to display cognitive task stimuli generated by a Silicon Graphics workstation. Cognitive stimuli (described below) were 11.38 × 10.03 cm and subtended a 5.29° vertical visual angle and a 4.67° horizontal visual angle.

Procedure

Within-subjects manipulations of vision (eyes open, eyes closed) and cognitive demand (no task, concurrent cognitive task) were factorially combined, yielding four experimental conditions (eyes open/cognitive task; eyes open/no task; eyes
closed/cognitive task; eyes closed/no task). These manipulations were chosen to create balance conditions that varied in difficulty and that were representative of situations encountered in day-to-day activity. Each condition was repeated four times, resulting in a total of 16 randomly ordered trials per participant. Testing sessions lasted approximately one hour.

Participants stood on the force platform in a natural stance, with the feet positioned shoulder-width apart. They were directed to relax and to allow the arms to suspend naturally and comfortably at their sides. Participants were further instructed not to speak, gesture, or make any large-scale voluntary movements (e.g., of the arms) during the postural stability measurement period. At the beginning of each trial participants assumed the aforementioned stance. Data collection was initiated following notification from participants that they were stable and ready to begin.

On half the trials (randomly ordered), no cognitive task was performed; on the remaining trials, a visuo-spatial working memory task was performed. In the cognitive task conditions, participants visualized a novel 3-D object (similar to the “mental rotation” figures used by Shepard & Metzler, 1971) projected on the flat-screen monitor for 10 s prior to postural sway measurement (see Figure 1). After 10 s, the figure disappeared. Participants were then instructed to either close their eyes or keep them open. Acquisition of 30 s of postural data then commenced. Participants were instructed to stand comfortably during data acquisition while visually “rehearsing” the shape (i.e., keeping the shape in working memory). After the 30 s period, participants were instructed to again look at the monitor, where a second figure appeared. The participant had to determine if the second figure was the same as the first figure by giving a “same”
or “different” verbal response (half of the cognitive task trials were the “same” and half were “different”). In order to increase the cognitive demand of the task, the second figure was visually identical to the first on 50% of the “same” trials, but rotated in any of three spatial axes for the remaining 50% of the “same” trials. Participants were not provided information about the proportion of trials on which the same figure would be displayed, but they were informed that the second figure could be a rotated version of the first figure. If the second figure was identical to the first but rotated, a correct response would be “same.” The rotation manipulation was intended to encourage participants to concentrate on the shape of the object. Novel figures were used on each cognitive task trial for a given participant. Each participant was presented the same set of figures (but in a different random order). No feedback on cognitive task performance was given. Participants were instructed to perform the cognitive task as accurately as possible.

Figure 2 depicts the experimental procedure for the cognitive task condition. On trials when no cognitive task was performed, the cognitive stimulus was removed from the monitor and participants were simply instructed to stand comfortably with their eyes open or closed while postural data were collected. Figure 3 depicts the experimental procedure for the no cognitive task condition.

**Data Analysis and Reduction**

There were two primary sets of dependent measures in this study, each sampled across all 4 experimental conditions. The within-trial standard deviation of the anterior-posterior (AP) and medial-lateral (ML) COP time series and the COP path length, a resultant measure that provides the distance traveled by the COP over the 30 s measurement period, were computed by Datapac 2000 and used as statistical descriptors.
of postural stability. The COP standard deviation measures the variability of postural sway, and path length measures the overall amount of postural sway. RQA was employed to provide multiple indices of the time-varying properties of postural sway, including measures of the degree of auto-correlation (% recurrence), randomness (% determinism), complexity (entropy), mathematical stability (maxline), and degree of non-stationarity (trend) in the spatiotemporal profile of the COP (Riley et al., 1999). All dependent measures were averaged over repeated trials in the same condition, yielding for each participant an average value of each dependent measure in each of the four experimental conditions.

Preliminary exploration of the data indicated that normality and variance assumptions of the classical analysis of variance (ANOVA) were violated. Distribution-free (i.e., non-parametric) methods are a reasonable alternative when sampling from non-normal populations or when other ANOVA assumptions are violated (Everitt, 1996). Transformation of the data in order to meet the assumptions of ANOVA is an alternative to non-parametric methods, which are generally less powerful than corresponding parametric techniques (Gravetter & Wallnau, 2002). However, typical transformation procedures that correct for deviations from normality do so at the expense of homogeneity of variances of the error variables (Dean & Wolfe, 1996). Moreover, square-root and logarithmic transforms of the present data failed to eliminate all of the violations of ANOVA assumptions. For these reasons, the effects of group, vision, cognitive task, and their interaction on postural stability (COP AP, COP ML, and COP path length) and the spatiotemporal dynamics of postural sway (% recurrence, % determinism, maxline, entropy, and trend) were assessed using the nonparametric Box-
Type Approximation technique (Brunner, Dette, & Munk, 1997). Like many other nonparametric procedures, such as the Mann-Whitney test (Mann & Whitney, 1947), the nonparametric Box-Type Approximation employs ranks of the measurements instead of the actual measurements. The Box-Type Approximation is based on an $F$ distribution and yields an $F$-like statistic, $F_N$. Brunner et al. showed that the Box-Type Approximation $F_N$ for higher-order factorial designs was (for small sample sizes) more accurate than and was (across small and large sample sizes) equally powerful to the Wald-type rank statistic developed by Akritas (1990; see also Akritas & Arnold, 1994; Akritas, Arnold, & Brunner, 1997; Thompson, 1991). An alpha level of .05 was used for all Box-Type Approximations.
CHAPTER 3

Results

Time Series Plots and Recurrence Plots

Figure 4 illustrates a typical COP time series for a PD and control participant. These data are consistent with previous observations that time series of healthy, adaptive physiological processes possess irregular, variable spatiotemporal dynamics, whereas time series of pathological processes possess rigidly regular spatiotemporal dynamics (Goldberger, 1997). Figure 4 clearly demonstrates greater COP regularity (i.e., a more pronounced oscillatory pattern) in the time series of the PD patient.

A recurrence plot is constructed by plotting a pixel at specific coordinates \((i, j)\) whenever pairs of data vectors are identified as close (i.e., recurrent) in \(d_e\)-dimensional, reconstructed phase space (Eckmann, Kamphorst, & Ruelle, 1987). Structure not observable in the one-dimensional time series can be identified as specific patterns within constellations of recurrent points in a recurrence plot (Webber & Zbilut, 1998). Recurrence plots for PD and control participants are shown in Figure 5. The recurrence plot of PD patient data has a greater proportion of darkened pixels, indicating that this PD patient has higher recurrence in the time series than the control participant. Furthermore, a higher number of line segments parallel to the main diagonal (short line segments parallel to the main diagonal are strings of vector patterns in the time series that repeat themselves multiple times over the observation period, implying determinism in the time series; Riley et al., 1999) can be seen in the recurrence plot of PD patient data.

Postural Stability
The Box-Type Approximation statistic revealed a main effect of group for all measures of postural stability. The standard deviation of the AP COP was significantly higher for PD patients ($M = 0.680$ cm, $SD = 0.524$ cm) than for the elderly, healthy control participants ($M = 0.197$ cm, $SD = 0.121$ cm), $F_N (1, 10) = 36.09, p < .05$. ML COP standard deviation was also significantly higher in PD patients ($M = 0.823$ cm, $SD = 0.700$ cm) than in the elderly, healthy control group ($M = 0.351$ cm, $SD = 0.066$ cm), $F_N (1, 10) = 18.05, p < .05$. This trend was also observed in path length. Distance traveled by the COP over the measurement period was significantly higher for PD patients ($M = 295.362$ cm, $SD = 96.387$ cm) than for elderly, healthy control participants ($M = 208.334$ cm, $SD = 31.740$ cm), $F_N (1, 10) = 7.96, p < .05$. The group effect for each of these measures is presented in Figures 6, 7, and 8. No other effects (vision, task, all possible group, vision and task interactions) on postural stability measures were significant.

**Spatiotemporal Profile**

Box-Type Approximations yielded a significant effect of group for AP % recurrence. Recurrence was greater for PD patients ($M = 9.090\%$, 256.338 data points, $SD = 4.366\%$, 123.121 data points) than healthy controls ($M = 5.370\%$, 151.434 data points, $SD = 3.411\%$, 96.162 data points), $F_N (1, 10) = 8.20, p < .05$. A significant group effect was also found for AP % determinism, in which the spatiotemporal profile for PD patients was less random ($M = 80.863\%$, 207.283 data points, $SD = 28.287\%$, 72.510 data points) than for the healthy control participants ($M = 52.679\%$, 79.774 data points, $SD = 30.557\%$, 46.274 data points), $F_N (1, 10) = 13.21, p < .05$. Mathematical stability (maxline) of the AP time series was found to be significantly greater for PD patients ($M = 2138$ data points, $SD = 1140$ data points) than for healthy controls ($M = 908$ data points,
Posture and PD

SD = 1165 data points), $F_N(1, 10) = 8.23, p < .05$. Finally, the deterministic structure of AP COP time series were significantly more complex (entropy) for PD patients ($M = 3.565$ bits, $SD = 1.698$ bits) than for healthy controls ($M = 1.983$ bits, $SD = 1.242$ bits), $F_N(1, 10) = 6.82, p < .05$. Figures 9, 10, 11 and 12 depict the AP group differences found for each of these four measures. No other effects (task, all possible group, vision, and task interactions) reached statistical significance.

Box-Type Approximations yielded a significant main effect of vision for % recurrence in the ML direction. Recurrence was greater in the eyes-open condition ($M = 10.109\%, 285.074$ data points, $SD = 2.847\%, 80.285$ data points) than in the eyes-closed condition ($M = 7.421\%, 209.272$ data points, $SD = 3.636\%, 102.535$ data points), $F_N(1, 10) = 6.26, p < .05$. Figure 13 illustrates this vision effect. No other group or task differences were observed in the ML direction.

Cognitive Task Performance

Overall performance on the cognitive task was evaluated in terms of the number of total correct responses (out of 8 cognitive task trials). Performance accuracy did not differ significantly for groups ($M$ for PD group = 77.13\%, $M$ for control group = 75.00\%), $t(10) = .183, p > .05$. Accuracy on the cognitive task trial did not vary as a function of rotation or non-rotation of the novel 3-dimensional shape ($M$ for rotated shape = 72.92\%, $M$ for non-rotated shape = 79.17\%), $t(11) = -1.00, p > .05$. 


CHAPTER 4

General Discussion

The purpose of this study was to determine the effects of PD, vision, and cognitive demand on postural stability. I predicted that individuals with PD would exhibit greater postural variability and a greater amount of postural sway than elderly, healthy controls. That prediction was confirmed. The PD group demonstrated higher COP standard deviations in both the AP and ML sway directions and greater COP path lengths. I also expected PD to be associated with higher values of recurrence and determinism. That prediction was confirmed for AP sway. Those findings indicate that the spatiotemporal profile for PD participants was characterized by stereotypical regularity (cf. Goldberger, 1997). Contrary to predictions, maxline and entropy of the COP time series were found to be significantly higher for PD participants. Those findings indicate that postural sway of PD patients was more mathematically stable and the deterministic structure of their postural sway was more complex than the postural sway of elderly, healthy control participants.

The prediction that randomness of postural sway would decrease in the absence of vision (Riley et al., 1999) was not confirmed, but there was the significant main effect of vision for ML percent recurrence (greater recurrence, i.e., nonlinear auto-correlation, with eyes open). Hypotheses concerning the effect of cognitive demand were not supported—there were no effects of cognitive task conditions on postural sway. The prediction that the disparity between PD and control participants would increase as the difficulty of the factorially combined manipulations increased was also not supported.
In general, the static posturographic method employed in this study, in conjunction with RQA, discriminated PD patients from elderly, healthy controls. The postural sway of the PD patients was more variable, yet generally more structured and deterministic. The significance of the results regarding the spatiotemporal profile of the COP time series, possible reasons for the absence of an effect of cognitive demand, implications for PD, and future research directions are discussed in subsequent sections.

**Spatiotemporal profile of the COP**

One assumption in most studies of postural control is that the variability of the COP is a reflection of postural stability. A number of researchers have cautioned that this assumption cannot be made without further consideration of the spatiotemporal dynamics of the COP (Newell, Kugler, van Emmerik, & McDonald, 1989; Newell, van Emmerik, Lee, & Sprague, 1993; Newell & Slifkin, 1998; Riccio, 1993; Riley, 2001; Riley & Turvey, 2002; Slifkin & Newell, 1999). The use of RQA in the present study yielded a broader picture of postural instability in PD than the use of variability measures alone would have provided.

The initial predictions regarding the COP spatiotemporal profile in this study were that PD would be associated with dynamics that were more regular (higher % determinism, higher % recurrence), less complex (lower entropy), and less stable (lower maxline) than sway from elderly, healthy controls. That prediction was based on the notion that healthy physiological processes are characterized by variable, complex behavior, whereas pathological processes are characterized by a loss of complexity and stereotypical regularity (Goldberger, Rigney, & West, 1990; Goldberger, 1996, 1997; Goldberger, Peng, & Lipsitz, 2002; West & Goldberger, 1987). In general, the results of
this study were consistent with that notion. RQA revealed that the COP time series of PD patients exhibited greater recurrence and greater determinism than the COP time series of the control participants. Greater recurrence and greater determinism indicate that the postural sway of PD patients was generally more regular and stereotypical than the sway of control patients (see Figure 4). The increased regularity of postural sway associated with PD may be related to an inability to adapt postural behavior to changing circumstances (Horak et al., 1992; Melnick et al., 1999; Rogers, 1990, 1991). In general, people with PD exhibit difficulties in initiating motor actions or in changing an ongoing action in response to changes in the environment. The present postural sway results are consistent with this well-documented feature of PD.

Contrary to predictions, however, the COP time series of PD patients yielded higher maxline and higher entropy values—their postural sway was more mathematically stable and more complex than the postural sway of control participants. There are several possible interpretations of these findings. Maxline is a measure of mathematical stability of the COP time series. Mathematical stability refers to the divergence of trajectories that begin at arbitrarily close initial conditions or, equivalently, to a system’s response to a small perturbation of its trajectory. (The maxline measure is inversely proportional to a measure termed the Lyapunov exponent; Webber & Zbilut, 1994.) In the original hypothesis formulated for the maxline measure, I equated mathematical stability and postural stability. That equation may have been incorrect. The properties of postural stability and mathematical stability were inversely related in the present study, since increases in COP standard deviation and path length (indicating decreased postural stability) were coupled with an increase in maxline. An alternative interpretation of the
maxline result is that increasing mathematical stability of postural sway may have reflected a compensatory strategy. That is, increasing mathematical stability of postural sway may reflect a means of countering the overall increase in sway and sway variability. A second possibility is that the increase in maxline was simply entailed by the increase in determinism—the COP time series for PD patients were categorically more regular and predictable. However, this possibility is not supported by the results of several individual participants in the present study who had time series with high determinism but comparatively low values of maxline.

Similarly, the opposite finding for entropy may be related to the way in which entropy was initially conceptualized. The extent to which the present results directly contradict the assertion that pathological physiological processes reflect a loss of system complexity (Goldberger, 1996, 1997; Goldberger et al., 1990, 2002; West & Goldberger, 1987) is dependent on the appropriateness of choosing to define “complexity” as the entropy value obtained in RQA. While entropy was characterized as a measure of the complexity of the deterministic structure of a time series (Webber & Zbilut, 1994, 1996), it is essentially a measure of the regularity of diagonal line lengths in a recurrence plot. As Goldberger et al. (2002, p. 24; emphasis theirs) pointed out, however, “increased irregularity does not imply increased physiologic complexity.” To the extent that entropy is a measure of the regularity of line segment distributions (i.e., of the deterministic structure of the time series), it may not be an adequate measure of complexity with which to evaluate the hypothesis that physiological complexity decreases with disease. Goldberger et al. (see also Riley et al., 1999) also pointed out that there is no agreement
regarding a single measure of system complexity—rather, complexity must be measured using “a ‘toolkit’ of extensive, still-evolving (and as yet undiscovered) metrics” (p. 24).

Tremor— involuntary, low-amplitude oscillations of body segments—is a hallmark characteristic of PD. Since force platforms are extremely sensitive, tremor could potentially contaminate postural sway measurements. There is no evidence that this occurred in the present study. Parkinsonian tremor typically has a frequency of 3 to 5 Hz, regardless of the body segment from which it is measured (Elble & Koller, 1990). As can be noted in Figure 4, the roughly oscillatory patterns that characterized postural sway in the PD patients occurred at a lower frequency (in the case of Figure 4, the large COP oscillations occurred at approximately 0.3 Hz). Furthermore, postural data were collected from PD patients during the on-phase of the medication cycle, when tremor is largely controlled.

**Absence of a cognitive task effect**

Allocation of attention during the performance of concurrent tasks is complex. It depends on a number of factors, including the nature of both the cognitive and postural task, the goal of each participant, and the instructions (Shumway-Cook et al., 1997). The complexity of attentional allocation complicates any inferences made about the absence of a cognitive task effect in the present study. However, there are a number of possible reasons that may account for the absence of an effect of the cognitive task on postural sway. One possible explanation is that the task was simply not cognitively demanding. However, participants exhibited, on average, 76% accuracy on the cognitive task. This indicates a moderate level of performance; if the task was not cognitively demanding performance accuracy should have been higher. A second possible explanation for the
absence of the cognitive task effect could be that attention and postural control do compete for resources, but postural control is given preference. To test that hypothesis the difficulty of postural performance would need to be varied, leading to the prediction that cognitive performance would decline in more difficult balance conditions. A final possible rationalization for the cognitive task findings may be that the posture task and the visuo-spatial memory task did not compete for the same attentional resources (Wickens, 1984). According to Wickens’ multiple resource model, tasks that do not compete for the same pool of attentional resources will not interfere (or otherwise interact) with each other.

It is also possible that the cognitive task was simply underconstrained. Participants were not instructed to perform mental rotations of the figures they visualized during postural measurement, but the second figure that appeared on the screen after postural measurement was, on 50% of the cognitive task trials, a rotated version of the initial figure. Those features of the task could have rendered it ambiguous for participants to perform, although errors on the cognitive task trials were uniformly distributed for rotated and non-rotated shapes.

Implications for Parkinson’s Disease

Postural instability is symptomatic of PD, particularly as the disease progresses. When balance becomes an issue for patients with PD, fall-related injuries, restriction of gait patterns and decreased mobility are common. These issues (particularly falling) represent major health care concerns in the United States and have negative psychological counterparts, such as fear of falling, which can result in a substantial decrease in the amount of a person’s functional activity. Balance control is, moreover,
fundamental to the control of other behaviors (Gibson, 1966; Riccio, 1993; Riccio & Stoffregen, 1988), including locomotion, manual manipulation (Riley et al., 1999), and social interaction (Shockley, Santana, & Fowler, 2003). Thus, when balance control is impaired, the impairment may spill over to other behaviors that require a stable postural background for their performance. Consequently, early detection of postural instability in PD and a more complete understanding of conditions in daily life that intensify that instability are fundamentally important.

The retropulsion test is used by physicians to provide a judgment of the presence or absence of postural instability in PD, but the retropulsion test cannot be used to objectively quantify the degree of postural instability present. Quantitative measures of postural instability are needed. Until recently, most of the methods used to quantify the severity of motor dysfunction in PD have focused on local measures of rigidity (Caligiuri & Galasko, 1992; Ghiko, Wiegner, Fang, Davies, Young, & Growdon, 1993; Kirollos, Charlett, O’Neill, Kosik, Mozol, Purkiss, Bowes, Nicholson, Hunt, Weller, Dobbs, & Dobbs, 1996; Prochazka, Bennet, Stephens, Patrick, Sears-Duru, Roberts, & Jhamandas, 1997; Watts, Wiegner, & Young, 1986). Measurement of rigidity is not a good proxy for postural stability, however, given that clinical interventions that reduce rigidity seem to have no effect on postural stability (Bloem et al., 1995; Horak et al., 1992; Melnick et al., 1999). Static posturography, coupled with analytical techniques like RQA, seems to present a more effective, objective means of quantifying postural instability than either the retropulsion test or measures of rigidity.

Some researchers have argued that dynamic posturography is more informative than static posturography (e.g., Bloem et al., 2001; Furman, Baloh, Barin, Hain,
Herdman, Konrad, & Parker, 1993). Dynamic posturography involves the measurement of postural responses to imposed balance perturbations. Dynamic posturography has been criticized on the grounds that the imposed perturbations (which often involve perturbation magnitudes 5 to 40 times larger than perturbations experienced during normal stance) are unnatural, and thus responses to the perturbations are unrepresentative of normal postural control (Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997). In addition, dynamic posturography does not always discriminate balance-disordered participants from controls. Horak, Nashner, and Nutt (1988) and Schieppati and Nardone (1991) found only minor differences between patients with PD and control participants in the execution of postural responses to an imposed perturbation. For example, the amplitude and distribution of tonic leg muscle EMG recordings was found to be within normal ranges when participants with PD attempted to maintain upright stance with and without vision (Schieppati & Nardone, 1991).

Static posturography is relatively easy and inexpensive to implement and involves less risk of falling during testing than dynamic posturography. Although the manipulations of vision and cognitive demand used in the present study did not appear to magnify differences between PD and control participants, static posturography did reliably detect overall group differences. Thus, the discriminatory power of static posturography and RQA in the present study—especially when considering the greater representativeness, simplicity, and safety of the technique—suggests that static posturography may be an effective means of quantifying postural instability in PD and other clinical conditions.
Future directions

The results of this study suggest that static posturography and RQA may be useful techniques for quantifying instability across different mobility stages of PD and for the establishment of objective criteria for diagnosing postural instability in PD. As previously noted, clinical diagnosis of postural instability is the primary distinction between H-Y stages 2 and 3. If criterion levels of postural instability can be established, then static posturography would be a more reliable means of diagnosing postural instability than the retropulsion test. Static posturography could also be used to determine if changes in postural sway variability or the spatiotemporal profile of postural sway accompany the presence of other identified points of progression in PD (i.e., symptom asymmetry or symmetry, increased muscle rigidity and bradykinesia, or gait problems). However, it may be worth noting that there was some data point overlap for PD and control participants in many of the dependent variables, which suggests that these groups were not completely dissociated using these indices.

A second possible direction for future research involves using static posturography and RQA as a quantitative evaluation of the effects of different treatment regimes for PD, such as pallidotomy or deep-brain electrical stimulation. Bronte-Stewart et al. (2002) showed that pallidotomy was associated with greater improvements in postural stability than pharmacological interventions (see also Melnick et al., 1999). High-frequency deep-brain electrical stimulation has been shown to alleviate PD symptoms such as rest tremor (Benabid, Pollak, Gervason, Hoffman, Gao, Hommel, Perret, & Rougemont, 1991; Benabid, Benazzouz, Hoffman, Limousin, Krack, & Pollak,
1998), but the effects of deep-brain stimulation on postural stability in PD remain to be explored.

One consideration when measuring postural stability in individuals with PD should be differences in uses of medications. All participants in the present study were prescribed levodopa-carbidopa, medications that enhance the effects of levodopa, dopamine agonists, or dopamine reuptake antagonists. Research by Rocchi et al. (2002) suggested that treatment with levodopa increases postural sway abnormalities by increasing the involvement of non-dopaminergic pathways, which results in the declining effectiveness of levodopa replacement therapy (i.e., dyskinesias and motor fluctuations may appear). A standardization of static posturography with respect to the clinical characteristics and medication schedules of patients may help to improve the sensitivity and utility of the technique, allowing abnormalities of postural stance to be detected even at very early stages of PD (Contin et al., 1996). Because of the adverse association with chronic levodopa treatment and the implication that many PD patients will suffer from the disease for the greater part of their lives, early detection of postural instability is an important issue for future research.

**Conclusion**

The effects of balance impairment can be dramatic. Presently our understanding of postural instability in PD is, at best, modest. This research provides a quantitative and objective evaluation of balance control in PD. The research is innovative in its combination of static posturography and newer analytical tools (RQA) for operationalizing postural stability. The finding that static posturography and RQA reliably differentiated the PD and control participants is promising. These techniques
may aid in earlier detection of postural instability in PD and should be considered as a useful adjunct to current clinical measures of motor dysfunction in patients with PD.
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Posture and PD

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APPENDIX A

Recurrence Quantification Analysis

In recent years there has been increased recognition that most physiological systems are complex, nonlinear, nonstationary, and noisy (e.g., Bassingthwaighte, Liebovitch, & West, 1994; Glass & Mackey, 1988; Goldberger, 1997; Murray, 1993; Riley & Turvey, 2002). In the field of postural control, this recognition has resulted in models of postural control and analytic techniques derived from stochastic physics and nonlinear dynamics (e.g., Collins & De Luca, 1993, Collins et al., 1995; Dijkstra, 2000; Duarte & Zatsiorsky, 2000; Newell et al., 1993; Newell, Slobounov, Slobounova, & Molenaar, 1997; Peterka, 2000; Riley, 2001; Riley, Balasubramaniam, Mitra, & Turvey, 1998; Riley et al., 1999; Riley & Clark, 2003; Rosenblum, Firsov, Kuuz, & Pompe, 1998; Rougier, 1998). One analytic technique that has demonstrated utility in postural control is recurrence quantification analysis (RQA) (see Riley et al., 1999; Webber & Zbilut, 1994, 1996). RQA was applied in the present study to the COP time series obtained from PD patients and elderly, healthy controls in order to quantify the spatiotemporal dynamics of postural sway.

RQA is a quantitative extension of the graphical method of recurrence plots introduced by Eckmann et al. (1987). Recurrence plots were originally designed to locate recurrent patterns (hidden rhythms) and nonstationarity (drift) in a time series. Recurrence plots (and RQA) do not impose constraints on data set size, stationarity or statistical distribution, and are effective even in the presence of noise and underlying state changes. Those characteristics make the technique ideal for the study of physiological data (Webber & Zbilut, 1994).
A recurrence plot is a topologically equivalent recreation of a univariate time series thought to be part of a larger, \( n \)-dimensional model. Thus, the first step in generating a recurrence plot is to recreate the \( n \)-dimensional model of the system dynamics. An \( n \)-dimensional space (termed *phase space*) is reconstructed from a measured, univariate time series using the *method of delays* (see, e.g., Sauer, Yorke, & Casdagli, 1991). The method of delays uses time-delayed copies of the measured time series as surrogate variables to stand in place of the other unmeasured (and usually unknown) system variables. Phase space reconstruction is an application of the *embedding theorem*, which states that the observed time series (which is a one-dimensional projection of the underlying system dynamics from the true, \( n \)-dimensional phase space of a nonlinear system) preserves certain invariant properties of the system dynamics, and those properties can be measured in the reconstructed phase space (Grassberger & Procaccia, 1983; Takens, 1981). The set of all data vectors that are embedded in the reconstructed phase space constitutes a trajectory through the reconstructed phase space. Invariant properties of the original dynamics are preserved in that trajectory.

The method of delays requires choosing a time delay, \( \tau \), to create the time-lagged copies of the measured signal that are used as surrogate dimensions of the reconstructed space. Phase space reconstruction also requires choosing an *embedding dimension*, \( d_e \), that is sufficient to “unfold” the \( n \)-dimensional dynamics of the measured system (i.e., \( d_e \) must be of a dimension greater than \( n \)). There are principled methods for choosing \( \tau \) and \( d_e \) (e.g., Abarbanel, 1996). For instance, \( \tau \) may be chosen based on the autocorrelation function (Weber, 2001) or the average mutual information function (Fraser & Swinney,
1986) of the measured time series, and a technique termed *false nearest neighbors analysis* may be used to determine \( d_e \). However, certain assumptions must be met by the data in order to use those methods. The autocorrelation and average mutual information methods fail if the time series is nonstationary. False nearest neighbors analysis is similarly disrupted by high levels of noise in the data. As indicated previously, data obtained from physiological systems are typically nonstationary and noisy, so those methods are often unsuitable for determining \( \tau \) and \( d_e \) for physiological data. While the assumptions of stationarity and noiselessness need not be met to generate a recurrence plot or to perform RQA, failure to meet those assumptions makes the determination of \( \tau \) and \( d_e \) challenging. Techniques used to determine these values for the present data will be described later in the appendix.

Once values of \( \tau \) and \( d_e \) have been selected and phase space reconstruction is completed, a characteristic of the data set called recurrence, or “neighborliness” (proximity in the reconstructed phase space) is defined by counting the number of data points within a sphere of some chosen radius, \( r \), when the sphere is centered around a given data point. The Euclidean distance in the reconstructed phase space between a given point \( i \) and every other point \( j = 1 \) to \( N \) (where \( N \) is the length of the trajectory in reconstructed phase space) is calculated. If the distance is less than or equal to \( r \), the points \((i, j)\) are considered recurrent. The distance calculations and determination of recurrence is computed for all \( i = 1 \) to \( N \) (i.e., each data point is compared to every other data point). The degree and nature of the recurrence in time series are specified in a recurrence plot (Riley et al., 1999), where each darkened \((i, j)\) coordinate represents a recurrent point in the reconstructed phase space. Recurrence represents an instance of
self-correlation in the data, and neighborliness in reconstructed phase space means the trajectory repeats itself over time.

There are a number of qualitative characteristics that can be derived from a recurrence plot, including homogeneity, drift, periodicity, and other small-scale texture in the phase space. Homogeneity is denoted pictorially by the uniform and homogenous distribution of recurrent points in the plot. Drift is the tendency of points in the plot to become more faint or absent as the distance from the main diagonal (where \( i = j \), i.e., a point is compared to itself and thus is necessarily identified as recurrent) increases. Drift in the recurrence plot indicates nonstationarity. If the density of recurrent points changes abruptly, a change in level is specified. Periodicity reflects a predominantly rhythmic structure in the data and is represented in a recurrence plot as long diagonal lines parallel to the main diagonal. Smaller scale textures to note in a recurrence plot include single, isolated recurrent points, short line segments, grouping of line segments, bands of white space and changes in the density of the recurrent points. Single and isolated recurrent points signify random behavior. This is contrasted by points falling on a line (parallel to the main diagonal). Such lines indicate entire sequences of data points that repeat themselves. Sequences of data points that recur indicate deterministic structure in the data—the trajectory revisits the same region of the reconstructed phase space at different times. If the line segments are diagonal but perpendicular to the main diagonal, vector sequences at different locations in the series are mirror images (imagine, for example, bisecting a perfect sine wave at a peak or trough—the two halves of the wave would be reflectionally symmetric about the bisection point). If the line segments are horizontal or vertical, isolated vector sequences match closely with a repeated string of vectors later in
Posture and PD

When line segments are grouped into regions of the plot, the inference is that the system is episodically visiting different areas of the reconstructed phase space, switching back and forth between them. Underlying level or state modifications are reflected in bands of white space. Finally, change in density of the recurrent points along an axis of the plot suggests that the dynamical regime has been altered. This is typically observed after a transient period.

While qualitative features of recurrence plots can be revealing, recurrence plots are more usefully described using a set of objective, quantitative measures. That was the motivation for developing RQA (Webber & Zbilut, 1994). The objective measures that comprise RQA include % recurrence, % determinism, maxline, entropy, and trend. Percent recurrence quantifies the percentage of the plot occupied by recurrent points. It is calculated by taking the number of recurrent points and dividing it by the total number of \((i, j)\) coordinates in a triangular half of the plot (because the plot is symmetrical about the main diagonal, all calculations are focused on just one of the two triangular areas). The distinction between points that are isolated and those that are organized in diagonal patterns is quantified by % determinism, which is the percentage of recurrent points that fall along upward diagonal line segments. Maxline is the length of the longest diagonal line parallel to the main diagonal, excluding the main diagonal. Maxline is inversely proportional to the largest positive Lyapunov exponent, which is, roughly speaking, a measure of the mathematical stability of the time series. High values of maxline indicate greater stability. Entropy is a measure of complexity of the deterministic structure of the time series. It is computed as the Shannon entropy of a histogram of line segment lengths (the number of observed upward diagonal lines of different lengths are counted and
distributed over integer bins of a histogram, where each bin represents a different line length),

\[ E = - \sum P_b \log_2(P_b) \quad (1) \]

where \( P_b \) indicates bin probabilities of all nonzero bins greater than or equal to the number of recurrent points defining a line (Weber & Zbilut, 1994). Trend is a measure of the paling of the recurrence plot away from the main diagonal. It is computed by finding the slope of the line of best for \% recurrence as a function of distance from the main diagonal. Non-zero trend is an indication of drift in the system. Values of trend close to zero indicate stationarity.

Together, visual inspection of the recurrence plot and RQA provide a robust means of studying the spatiotemporal dynamics of a time series. The primary drawback of the technique concerns the difficulty of reconstructing the \( n \)-dimensional phase space. Selecting appropriate values of the input parameters (embedding dimension, delay, radius) demands a thorough understanding of the system under scrutiny. As such, RQA remains an uncalibrated, though promising, technique (Weber & Zbilut, 1998).

In order to determine appropriate input parameters for time lag, embedding dimension, and radius, the response of RQA output measures over systematic changes in the input parameters was observed (Zbilut & Webber, 1992). RQA measures were computed for a range of typical postural sway parameter settings (cf. Riley et al., 1999). From this range, a setting was chosen that yielded smooth (i.e., not large, discontinuous jumps) changes in the RQA output measures over changes in input parameters (Riley et
In addition to smooth % recurrence responses, the radius parameter should be set to a value so that identified recurrence is local in the reconstructed phase space, rather than global (Riley et al., 1999).

In order to visually evaluate the smoothness of % recurrence over changes in input parameters, three-dimensional surface plots were created for several possible embedding dimensions (6-10). Each of these plots projected a range for radius (14-32) and time lag (6-10). Surface plots were compared and flat, stable areas of the plots where % recurrence was relatively low (i.e., recurrence was local) were identified. RQA was run in order to explore the effect of an observed radius value on % determinism, which should not saturate at the floor of 0% or ceiling of 100%.

Based on the surface plots and these guidelines, both anterior-posterior and medial-lateral COP time series were embedded in a space of $d_e = 8$, using the measured COP signal and time-lagged copies of that signal with a delay $\tau = 9$ as coordinates of the reconstructed phase space. Smooth areas of the surface plots supported selection of a radius of 32% of the mean Euclidean distance separating points in the reconstructed phase space. The number of successive points required to identify a parallel line segment was set to 2. The five RQA measures were then computed, averaged across trials per condition for each participant and submitted to nonparametric ANOVA-type Box-Approximations with vision, cognitive demand, and group as independent factors.

In order to confirm the appropriate choice of parameter settings and to rule out the possibility of artifactual results, the RQA results attained were compared to those obtained from randomly shuffled data (samples were randomly re-ordered to create new time series) under the same input parameters (Theiler, Eubank, Longtin, Galdrikian, &
Farmer, 1992; Webber & Zbilut, 1994, 1998). When shuffled, any structure found in the reconstructed phase space should be destroyed, which would indicate that the originally observed structure was dependent upon the original sequential order of the data points and was not a statistical artifact. Randomization of the present data resulted in substantial drops in each of the RQA measures (i.e., determinism for all sampled trials was less than 1%). Further, the recurrence plots depicted homogenous typologies and did not resemble those for the intact data (see Figure 14). The outcome of this procedure supports the conclusion that the results obtained under the present parameterization reflect the true properties of the temporal evolution of COP and that the COP dynamics contain a degree of deterministic structure (Riley et al., 1999).
FOOTNOTE

1. On-phase periods of the medication cycle describe the period when the patient's medication is working. Movements are normal or almost normal and the patient is in a relative state of good motor function. However, after 2 to 5 years, almost 50% of PD patients notice that an individual dose of carbidopa/levodopa (Sinemet) does not last until the next dose of carbidopa/levodopa (National Parkinson’s Foundation, n.d.). The individual dose of carbidopa/levodopa "wears off," or "wears down." This “wear down” is called the off-phase of the medication cycle. The first morning dose of carbidopa/levodopa is usually the most effective—it is least likely to "wear off."
**Table 1.**

*Patient Summary (n = 6)*

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>S2</th>
<th>S9</th>
<th>S38</th>
<th>S39</th>
<th>S40</th>
<th>S41</th>
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Table 2.

*Medication Summary (n = 6)*

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Figure 1. Example of cognitive task stimulus.
Figure 2. Apparatus and an example of the cognitive task procedure.
Figure 3. Apparatus and an example of the no cognitive task procedure.
Figure 4. A 30 s sample of a typical AP COP time series for PD (top) and control (bottom) participants. The same time series are presented in Figure 5 as a recurrence plots.
Figure 5. A typical recurrence plot for PD (top) and control (bottom) participants. Note the presence of diagonal line segments parallel to the main diagonal in the recurrence plot of the PD patient’s data, indicating higher determinism in that COP time series.
Figure 6. COP standard deviation group effect in AP direction.
Figure 7. COP standard deviation group effect in ML direction.
Figure 8. COP path length group effect.
Figure 9. % recurrence group effect in AP direction.
Figure 10. % determinism group effect in AP direction.
Figure 11. Mathematical stability (maxline) group effect in AP direction.
Figure 12. Complexity (entropy) group effect in AP direction.
Figure 13. % recurrence vision effect in ML direction.
Figure 14. A recurrence plot for a randomly shuffled time series. Note the absence of structure in the plot and the homogenous typology of the recurrent points.