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Original article

# The relationship between intermittent limit cycles and postural instability associated with Parkinson's disease

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**Abstract**

*Background*: Many disease-specific factors such as muscular weakness, increased muscle stiffness, varying postural strategies, and changes in postural reflexes have been shown to lead to postural instability and fall risk in people with Parkinson's disease (PD). Recently, analytical techniques, inspired by the dynamical systems perspective on movement control and coordination, have been used to examine the mechanisms underlying the dynamics of postural declines and the emergence of postural instabilities in people with PD.
*Methods*: A wavelet-based technique was used to identify limit cycle oscillations (LCOs) in the anterior–posterior (AP) postural sway of people with mild PD ($n = 10$) compared to age-matched controls ($n = 10$). Participants stood on a foam and on a rigid surface while completing a dual task (speaking).
*Results*: There was no significant difference in the root mean square of center of pressure between groups. Three out of 10 participants with PD demonstrated LCOs on the foam surface, while none in the control group demonstrated LCOs. An inverted pendulum model of bipedal stance was used to demonstrate that LCOs occur due to disease-specific changes associated with PD: time-delay and neuromuscular feedback gain.
*Conclusion*: Overall, the LCO analysis and mathematical model appear to capture the subtle postural instabilities associated with mild PD. In addition, these findings provide insights into the mechanisms that lead to the emergence of unstable posture in patients with PD.


*Keywords:* Balance; Limit cycle; Parkinson's disease; Posture; Wavelets

## 1. Introduction

Parkinson's disease (PD) is a progressive, neurodegenerative disorder which compromises both motor and cognitive performance. Difficulty maintaining upright stance, a common motor symptom, appears to manifest early in PD[1] and increases in severity as the disease progresses. Although estimates vary across studies, it is generally accepted that between 50% and 70% of individuals with PD have fallen at least once.[2–5] Many of these individuals suffer debilitating injuries from their fall, drastically reducing their mobility, ability to perform daily activities, and overall quality of life.

### 1.1. Postural instabilities that occur with PD

Many factors such as muscular weakness, changes in the short- and long-loop postural reflexes, varying postural reactions to perturbation, and reduced anticipatory postural responses have been associated with postural instability and increased fall risk in people with PD.[6] Changes in postural stability associated with aging and disease are often assessed using the center of pressure (CoP) trajectory that is captured while an individual stands on a force plate. The CoP is the point location of the vertical ground reaction force vector. Declines in postural stability associated with PD have been observed in both the magnitude- and time-dependent dynamics of postural

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sway (assessed using the CoP trajectory). In regard to the magnitude of sway, it is consistently reported that, under a variety of manipulations such as standing with eyes open versus eyes closed or standing with an altered base of support, people with PD exhibit more postural sway than neurologically-intact individuals. The typical interpretation of this finding is that the increased sway is indicative of a decrease in balance stability.[7,8]

There are limitations when interpreting postural stability using only sway magnitude data. First, the implicit assumption that less sway is indicative of greater stability may not always be correct since some degree of extraneous body movement contributes to postural flexibility.[9] In contrast, adopting a rigid posture may hinder an individual's ability to respond to possible threats to balance.[10] For example, when balance is perturbed an individual cannot respond or recover as well without some flexibility and natural sway. Second, basic assessments of sway magnitude do not provide information describing the dynamics of CoP movement. It is important to note that the CoP is a collective variable that captures movement of all of the body's degrees of freedom. The underlying temporal evolution of movements in a variety of body segments provides information regarding how the body integrates multiple degrees of freedom into the completion of various tasks.[9] This temporal structure cannot be seen when assessing sway by taking spatial measures such as an average. Measures that examine the structure of postural sway provide valuable information regarding disease-related changes in the flexibility and adaptability of the postural system.

Measures of entropy have been an increasingly popular technique to assess the structure of postural sway.[11] Entropy measures essentially provide information regarding the complexity of the time series. Higher values of entropy indicate the signal is more complex, while lower values indicate the signal is more regular or periodic in nature. In general, more complex sway has been interpreted to mean that more of the body's degrees of freedom are being used to maintain stance (a less rigid posture is being adopted) and is therefore considered to be a signature of a healthy postural system. People with PD typically (but not always) exhibit more regular CoP signals compared to typically aging adults.[12] For example, Maurer et al.[12] found an abnormally large 1 Hz oscillatory sway pattern in people with PD. More oscillatory (sinusoidal) and deterministic patterns of sway suggest that postural complexity may be reduced in individuals with PD. This interpretation is consistent with the loss of complexity hypothesis proposed by Lipsitz and Goldberger.[13] According to this hypothesis, physiological systems degrade with disease, resulting in less complex biophysical signals; whereas under healthy conditions, the biophysical signals that emerge from the interconnected physiological systems of the body naturally have a rich and complex structure. As mentioned above, in the case of PD, more oscillatory sway dynamics could indicate postural rigidity.

Non-linear signal measures such as entropy have proven to be a valuable tool to assess the underlying dynamics of postural control. These tools have helped redefine the understanding of movement variability and how this variability relates to the adaptability and flexibility of the postural system. However, these measures cannot capture the underlying mechanism associated with increased oscillatory patterns. Mathematical models of posture (described below) are needed to understand how sway behavior is affected by neurophysiological factors such as neuromuscular feedback gain, time-delay, muscle stiffness, and muscle damping. In this paper, we build upon previous dynamical systems postural research with a newer wavelet-based technique to capture limit cycle oscillations (LCOs) in the postural sway of people with PD. LCOs are self-sustained, periodic motions which arise in many systems with time-delayed feedback.[14–24] In the postural domain, LCOs have been suggested to exist in mathematical models of individuals who experience increases in sensory delays and feedback gains.[25–29]

There are several advantages to assessing LCOs in patients with neurological disease. First, unlike measurements such as root mean square (RMS) or entropy, LCOs can be used to directly interpret the emergence of postural instability. For example, as discussed above, directly interpreting postural stability using more traditional linear and non-linear methods can be challenging. However, using mathematical models, previous research has shown that LCOs are a marker of dynamic instability of upright posture.[25–29] These models ultimately help us interpret experimental data by identifying the mechanisms that lead to potentially unstable postural behaviors such as LCOs. Second, because tremor in people with PD can often be intermittent and change as a function of various states such as anxiety or task demand, using measures such as wavelets that can capture transient changes in the dynamics of postural sway may better assess the emergence of postural instability.

Declines in postural control associated with PD have been well documented to occur even in people who were recently diagnosed. In the first chapter of the 1817 book *An Essay on the Shaking Palsy*, Dr. James Parkinson[30] states that soon after subtle symptoms are found in the control of the hand and arm, postural symptoms begin to manifest. According to Parkinson, "After a few more months, the patient is found to be less strict than usual in preserving an upright posture, this being most observable whilst walking, but sometimes whilst sitting or standing" (p. 4).[30] The postural changes observed by Dr. Parkinson, and commonly observed by neurologists today, are very salient as the disease progresses. More recently, studies are beginning to examine whether slight postural changes can be observed during the relatively long prodromal phase of the disease. Maetzler and colleagues[31,32] have documented that changes in postural control were, upon reflection by the patient, one of the subtle symptoms they noticed before being diagnosed. Additionally, Maetzler and colleagues[32] found that, when placed in challenging body orientations, postural changes are observed in people at risk of developing PD. Interestingly, the postural changes observed in these at-risk people appear to be related more to the smoothness rather than the magnitude of movement. Thus, measures which examine the time-dependent dynamics of posture, like the LCO measure described here, may be better able to capture the early postural changes in people with PD, and may ultimately provide an opportunity to develop early clinical markers for PD.