Research Article

Assessment of postural instability in patients with Parkinson's disease

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Abstract Postural instability is one of the most disabling features of idiopathic Parkinson's disease (PD). In this study, we focused on postural instability as the main factor predisposing parkinsonians to falls. For this purpose, changes in sway characteristics during quiet stance due to visual feedback exclusion were studied. We searched for postural sway measures that could be potential discriminators for an increased fall risk. A group of 110 subjects: 55 parkinsonians (Hoehn and Yahr: 1–3), and 55 age-matched healthy volunteers participated in the experiment. Their spontaneous sway characteristics while standing quiet with eyes open and eyes closed were analyzed. We found that an increased mediolateral sway and sway area while standing with eyes closed are characteristic of parkinsonian postural instability and may serve to quantify well a tendency to fall. These sway indices significantly correlated with disease severity rated both by the Hoehn and Yahr scale as well as by the Motor Section of the UPDRS. A forward shift of a mean COP position in parkinsonians which reflects their flexed posture was also significantly greater to compare with the elderly subjects and exhibited a high sensitivity to visual conditions. Both groups of postural sway abnormalities identified here may be used as accessible and reliable measures which allow for quantitative assessment of postural instability in Parkinson's disease.

Keywords Parkinson's disease - Elderly - Posture - Balance - Postural stability - Falls

Introduction

Epidemiological studies confirmed that falling is very common in PD patients and up to 90% of patients would fall at some stage or the other (Koller et al. *1989*; Ashburn et al. *2001*; Playfer *2001*; Stolze et al. *2004*). Therefore, assessment of balance in standing is a key component of the clinical evaluation for people with idiopathic Parkinson's disease (PD). The assessment enables clinicians to determine the degree to which they need to address fall prevention. The occurrence of falls is a potentially devastating and disabling problem for many individuals with PD which leads to loss of functional independence and social isolation. Gaining a better understanding of impairments in postural stability occurring with disease progression is imperative for the maintenance or improvement of a PD patient's quality of life. Studies are required which accurately identify fall risk factors and target intervention to the identified deficit areas. Complex knowledge of changes in the spontaneous sway characteristics can provide a basis for this understanding (Rocchi et al. 2002, 2006).

Force plate posturography is an easy and safe method that is commonly used in contemporary laboratories and can furnish insights into the physiological correlates of postural stability. However, the diagnostic value of postural sway, represented by this method as foot center of pressure (COP) motion, is frequently questioned. The problem of identifying posturographic instability measures in the elderly and in patients with neurodegenerative disease remains unsolved (Mitchell et al. 1995; Lauk et al. 1999; Bosek et al. 2005; Rocchi et al. 2006). Although, most of these studies were methodologically rigorous and promising for investigation of the dynamics underlying postural sway characteristics, they have not yet entered clinical practice and most clinicians rely on crude but effective tests for propulsion or retropulsion to determine postural stability (Visser et al. 2003). So far, the output measures of force platform posturography usually suffer from poor sensitivity for detecting postural problems and a lack of relevance to pathophysiological mechanisms of the disease. Typically, the data were obtained from a relatively small but diverse patient population with markedly differing degrees of motor symptoms. Also questionable is the compatibility of results obtained under different experimental designs in different laboratories.

Analysis of postural stability impairments in Parkinson's disease is very demanding. The identified age-related decline in posturographic indices are usually confounded with the additional effects associated with the disease and its treatment (Rocchi et al. 2006). Large-scale comparative posturographic studies are required to quantify postural instability predictors. The present study was undertaken to gain better insight into the discriminating power of different COP measures in order to isolate parameter(s) which appear to be sensitive to postural instability in the PD patients. The main objective of this study is to determine spontaneous sway characteristic abnormalities in well-diagnosed PD patients that could be considered as a revealing index of postural balance impairments.

Methods

The research was accepted by the Senate Ethics Committee of the Katowice Academy of Physical Education. A group of 110 subjects (age range 42–82 years) took part in the research. Prior to testing, the purpose of the study was explained to the subjects and informed consent was obtained. The patients underwent a detailed clinical evaluation by a physician trained in neurology. The assessment included a complete history and medication review, with attention to medical conditions and drugs associated with an increased risk of falls.

Research participants were PD patients of the Outpatient Neurological Clinic of Advanced Age, at the Central Clinic Hospital of Silesian Medical School in Katowice. The PD group consisted of 55 subjects (20 females and 35 males) in the age range 42–82 years (mean age: 64.6 ± 8.9 years) with a diagnosis of idiopathic Parkinson's disease; mean duration of disease was 5.5 ± 4.4 years. Hoehn/Yahr disease staging among patients was: 12 scored at stage I, 33 at stage II, and 10 at stage III. Subjects who scored greater than 3 on the Hoehn/Yahr scale and those with dyskinesia or motor fluctuations above grade 3 according to the unified parkinson's disease rating scale (UPDRS) were excluded from the study. Subjects were also not included if they exhibited dysfunctions affecting balance or musculoskeletal disorders limiting locomotion or balance. All patients were tested in the morning during the ON phase of their medication cycle (1–2 h after taking medication).

The comparison group consisted of the same number of gender- and age-matched healthy subjects ($N = 55$, 20 females and 35 males). The mean age of the group was 64.3 ± 7.9 years. Medical evaluation of the subjects reported no neurological or orthopedic disorders that could affect the posturographic testing and none had been treated with psychotropic drugs.

Subjects were asked to stand barefoot on the force platform in a comfortable stance. All subjects chose an open stance with feet apart, slightly turned out. To ensure that this position remained constant across trials, tracings were taken of foot placement and subjects were required to remain within these tracing during both trials. The quiet stance data were acquired with eyes open (EO) and eyes closed (EC). Two 30-s trials were separated with a rest break to avoid fatigue or boredom. In the EO trial, subjects looked at a fixation point located on the wall 1.6 m above the floor, 2 m in front of them. The fixation point was the "x" sign encircled, with an 18 cm black circle.

Excursions of the COP (postural sway) were assessed by a tensometric force plate (QFP Medicapture, France). All data were collected by pentium-class personal computer via the 16-bit analog-to-digital interface with a sampling frequency of 40 Hz. Analysis of the data involved comparison of the major sway measures (Takagi et al. 1985; Winter 1995; Raymekers et al. 2005) in order to isolate the most reliable parameters describing impairments in postural stability.

Repeated measures analysis of variance (ANOVA) was used to compare variables between PD patients and control subjects. Correlation analyses between COP measures and patients' scores on both the Hoehn and Yahr Disability Scale as well as on the unified parkinson disease rating scale (UPDRS) were performed across conditions with the non-parametric Spearman's rank test and Kendall's tau test (Statistica v. 5.0, StatSoft, USA).

Results

Statistical analysis of the collected data exhibited no significant differences in all COP measures between male and female subjects from both groups. Therefore, the data were then pooled for each group and the subsequent analysis (2 × 2 repeated measure ANOVA) involved comparison of group means for eyes open (EO) and eyes closed (EC) conditions.

Total sway path length

In the PD group, the mean sway path length was equal to 474.3 ± 295.3 mm while measured with eyes open and increased up to 686.1 ± 411.6 mm in the EC condition. In the control group, the mean path length increase was from 310.9 ± 124.6 mm (EO) to 433.8 ± 172.5 mm while standing with eyes closed. Eye closure resulted in a 45% increase of the total path length in the PD patients and only a 25% increase in the control group. The ANOVA showed both a significant group effect ($F_{1,108} = 17.53$; $P < 0.000006$) and vision effect ($F_{1,108} = 99.96$; $P < 0.000001$). Also significant was group and vision interaction ($F_{1,108} = 7.05$; $P < 0.01$). The results of this analysis are depicted in Fig. 1.

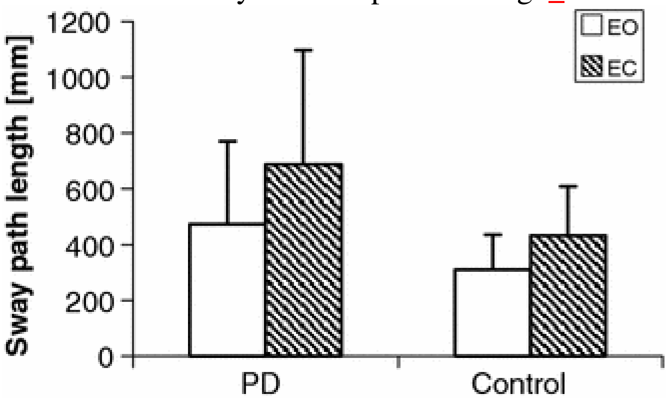

Fig. 1 Mean (±SD) of the sway path length during quiet stance in parkinsonian (*PD*) and *control* subjects while standing with eyes open (*EO*) and eyes closed (*EC*)

Antero-posterior (AP) sway path length

This statistical analysis examines the effect of vision on antero-posterior path length. In the PD group, the mean sway path in the AP direction increased from 345 ± 239 mm (in EO) to 524.3 ± 346.3 mm while tested with eyes closed. On the other hand, in the control group eye closure resulted in a more modest lengthening of the AP sway path from 241.8 ± 106.5 mm to 363.2 ± 145.1 mm. Results are shown in graphic form in Fig. 2. The main effects of both group ($F_{1,108} = 10.27$; $P < 0.002$) and vision ($F_{1,108} = 111.38$; $P < 0.000001$) were statistically significant. The interaction of both factors was also significant ($F_{1,108} = 4.15$; $P < 0.05$), proving a different sensitivity for each group for vision conditions.

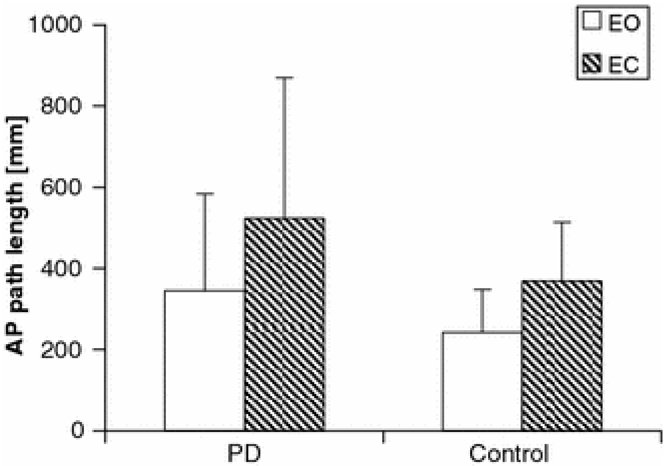

Fig. 2 Antero-posterior sway path length (mean ± SD) in *PD* and *control* groups in static posturographic test with eyes open and eyes closed

Sway path length in the mediolateral (ML) plane

Figure 3 shows lateral sway path lengths in both groups under EO and EC conditions. ANOVA results confirmed that both group and vision have very significant effects: group ($F_{1,108} = 30.84$; $P < 0.000001$) and vision ($F_{1,108} = 49.44$; $P < 0.000001$). Generally, the mean values of ML path length were markedly higher in the PD group. The means in this group were 253.4 ± 155.2 mm in EO and increased to 337.1 ± 196.5 mm in EC. The effect of vision was highly significant ($P < 0.000001$). In the control group, the increase of the ML path length due to eye closure was also significant ($P < 0.03$) at 147.6 ± 53.5 mm and 173 ± 77.6 mm in EO and EC conditions, respectively. It is worth noting that a statistically significant group and vision interaction for the ML path length was found ($F_{1,108} = 14.15$; $P < 0.0003$). In the control group, in EC the ML path length increase did not exceed 17% as compared to quiet standing with eyes open, whereas the PD patients were more susceptible to the vision exclusion which resulted in an increase in ML sway path length in excess of 57%.

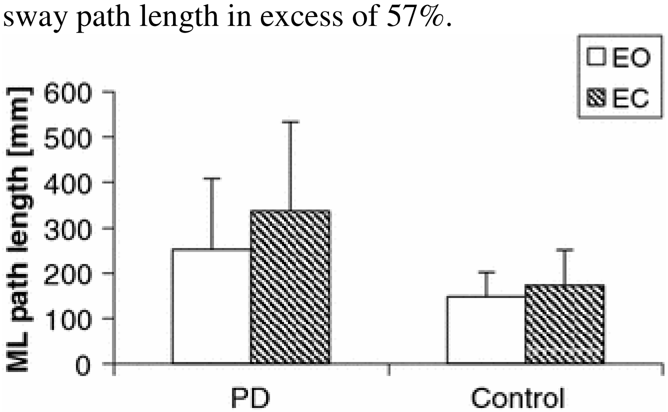

Fig. 3 Mediolateral sway path length (mean ± SD) in *PD* patients and *control* subjects

Spontaneous sway area

Subjects' gender had no significant effect ($P < 0.07$) on spontaneous sway area, but both of the double interactions, group and vision ($F_{1,106} = 5.76$; $P < 0.02$) and gender and vision ($F_{1,106} = 4.32$; $P < 0.04$), show statistical significance.

The 2 × 2 ANOVA confirmed significant differences in mean sway area in both groups ($F_{1,108} = 15.84$; $P < 0.0002$). The changes in the sway area are depicted in Fig. 4. The area of spontaneous sway under EO in the patient group was 329.7 ± 309.6 mm^2 whereas the sway area in the controls was significantly lower 179.5 ± 114.1 mm^2. Under EC testing only in the PD group did the sway area increase significantly, to 511.2 ± 508.06 mm^2 ($F_{1,108} = 18.41$; $P < 0.00004$), whereas in the control group the mean area measured under the same testing conditions increased only insignificantly ($P < 0.13$), to 239.6 ± 170.8 mm^2. The effect of vision was different in each group studied, as shown by the statistically significant group and vision interaction ($F_{1,108} = 4{,}64$; $P < 0.04$). Post-hoc analysis (LSD test) showed that the increase in the control group had not reached the established level of significance.

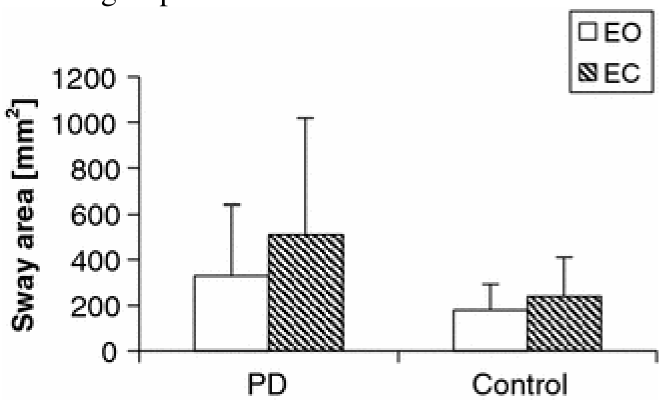

Fig. 4 Sway area (mean ± SD) in the group of *PD* patients and the *controls* while standing quiet with eyes open and eyes closed

Antero-posterior sway range

This analysis examined the changes in sway range. The ANOVA results followed by post-hoc LSD test showed that sway ranges in the AP direction were strongly affected by visual condition. In the group of PD subjects, the observed increase was statistically significant ($F_{1,108} = 10.47$; $P < 0.002$). The mean value of the AP sway range was equal to 26.7 ± 9.7 mm and 21.0 ± 7.3 mm, in PD and control subjects, respectively. Exclusion of the visual input resulted in decline in postural stability in both groups that was evidenced by an increase of AP sway range in the PD group to 34.3 ± 14.6 mm ($F_{1,108} = 62.95$; $P < 0.000001$). AP sway range also increased with statistical significance in the control group to 28.3 ± 10.1 mm ($P < 0.0001$). Changes in mean AP sway range for both groups are depicted in Fig. 5.

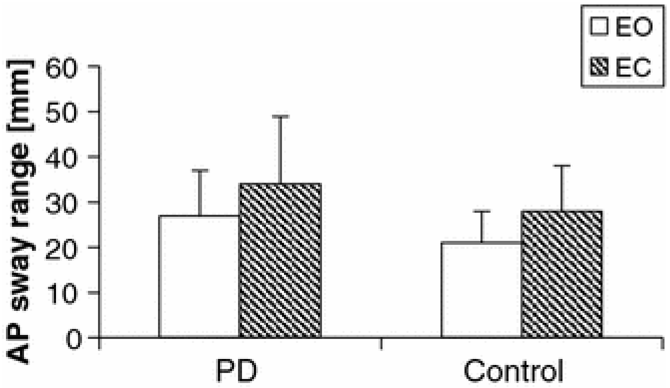

Fig. 5 Antero-posterior (means and standard deviations) sway range in groups of *PD* patients and *control* subjects while standing quiet with eyes open and eyes closed

ML sway range

The repeated measure ANOVA showed significant main effects for both group ($F_{1,108} = 17.09$; $P < 0.0001$) and vision ($F_{1,108} = 13.79$; $P < 0.0003$). The mean lateral sway range measured with eyes open was 20.3 + 13.3 mm in the PD group, which is significantly higher as compared to the control group mean of 14.8 ± 5.4 mm. Under the eye-closed condition, the mean ML sway range increased to 26.4 ± 16.7 mm in the PD group ($P < 0.000005$) whereas in the control group only an insignificant ($P < 0.65$) increase was noted (Fig. 6).

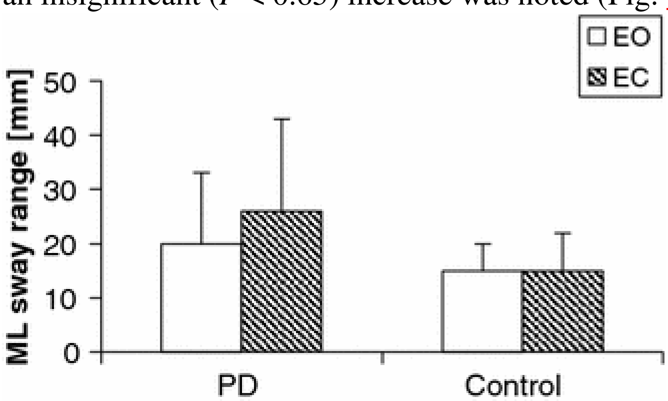

Fig. 6 Mediolateral sway range (mean + SD) in *PD* patients and *control* subjects while standing quiet with eyes open (*EO*) and eyes closed (*EC*)

Mean COP position in the AP direction

The most informative measure of upright stance postural stability is the mean COP position in the AP direction as measured in relation to an anatomical landmark (in our case from the tuberosity of the tendocalcaneus). The results of statistical analysis showed that the mean COP position in PD patients was significantly shifted forward in comparison with the control group. The mean value of this parameter was 102.5 ± 12.0 mm in the PD group, significantly ($F_{1,108} = 3.98$; $P < 0.05$) higher than the control subjects' value of 98.8 ± 11.2 mm.

Visual condition proved to exert a strong effect on the preferred COP position ($F_{1,108} = 44.52$; $P < 0.000001$). In the PD group, eye closure resulted in an additional forward shift of COP position in excess of 6 mm (mean value 108.7 ± 13.4 mm, $P < 0.000001$). In contrast, in the control group, the mean COP position as measured under the same EC condition was shifted forward only by 4.8 mm (103.6 ± 12.9 mm). The shift of the preferred COP position in the older adults was also highly statistically significant ($P < 0.00008$). The results of this analysis are summarized in Fig. 7.

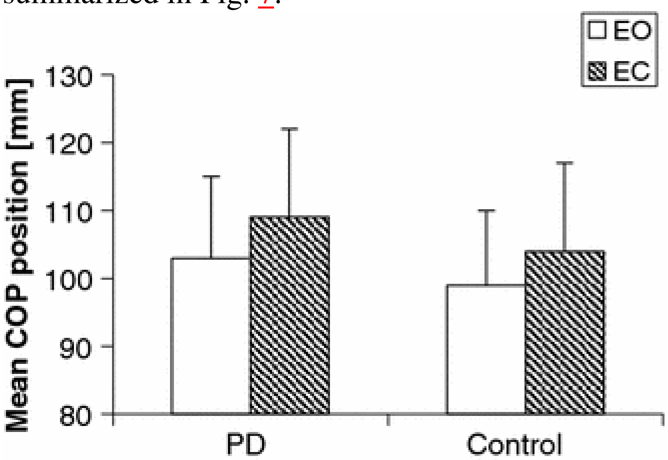

Fig. 7 Mean (±SD) antero-posterior *COP position* (preferred *COP position* within the base of support in relation to the tuberosity of tendocalcaneus) during quiet stance in *PD* subjects and in *control* group

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Relationship between PD stage, falls and sway measures

Thirteen of our PD patients reported rare falls in the recent year. Most of them (ten subjects) scored at stage 3.0. in the Hoehn/Yahr scale whereas the rest three subjects experienced falls at an earlier stage of the disease (Hoehn/Yahr 1.5, 2, 2.5). Results of a nonparametric correlation analysis (Kendall's tau test) between falls unrelated to freezing and different sway measures as well as components of the UPDRS rating scale are depicted in Table 1. Additionally, correlation tests (Spearman's nonparametric correlation test and Kendall's tau test) were performed between different sway measures and disease stage scored by the Hoehn/Yahr scale. Spearman's test demonstrated a significant correlation ($R = 0.29$, $P < 0.032$) between disease stage and range of mediolateral sway under EO conditions. ML path length also exhibited the same tendency, but the result fell slightly short of the level of significance ($P < 0.06$). The next tests were conducted based on Kendall's rank correlation coefficient. In this test, the significant positive value for Kendall's tau indicates that the tested variables exhibit a rank correlation. Similar to Spearman's test, only two spontaneous sway indices i.e., the mediolateral sway range ($z = 2.39$, $P < 0.02$) and the ML path length ($z = 1.98$, $P < 0.05$) measured under eyes open conditions correlated significantly with Hoehn and Yahr disease severity score.

Table 1 Results of correlation analysis ($N = 55$ parkinsonians in the early stage of the disease) between falling unrelated to freezing (UPDRS item 13) and different components of the UPDRS as well as COP measures

Pair of variables	Kendall Tau correlations

	Kendall Tau	*z*	*P* level
Falls and Hoehn/Yahr score	0.487	5.26	0.000001
Falls and ME score	0.47	5.10	0.000001
Falls and Gait (UPDRS item 29)	0.51	5.49	0.000001
Falls and Rigidity (item 22)	0.402	4.33	0.000015
Falls and Postural stability (item 30)	0.426	4.59	0.000004
Falls and COP ML range EO	0.184	1.99	0.047
Falls and COP ML range EC	0.189	2.04	0.042
Falls and Sway area EC	0.184	1.99	0.047

ME Motor Section of the UPDRS

Discussion

In the present study, we focused on the spontaneous sway measures which estimate descriptive statistics of the COP and are commonly assessed in clinical practice. Since the causes of postural instability are multifactorial and the parkinsonian population is diverse, there is likely to be no homogeneous effects on posturographic results. Therefore, the results of the studies published so far were often contradictory and limited. For instance, Schiepatti and Nardone 1991 analyzed several COP measures including position of foot center of pressure, average sway area, and length of sway path while standing quiet with eyes open or closed. The only significant finding in parkinsonians was represented by a shift in the position of the COP. Other research groups reported a decrease in postural sway in PD patients as compared to aged-matched controls (Horak et al. 1992). There are also reports of increased amplitude of spontaneous sway in PD patients (Gregoric and Lavric 1977; Kitamura et al. 1993). Some authors claim that the antero-posterior sway characteristics in PD patients are not significantly different when compared with age- and sex-matched controls (Viitasalo et al. 2002). There is also growing evidence for the hypothesis that mediolateral instability is an important posturographic marker of functional balance impairment in Parkinson's disease (Mitchell et al. 1995; Viitasalo et al. 2002; Rocchi et al. 2006).

Our results of static posturography showed significant differences between PD patients and healthy elderly in most sway parameters: sway area, sway ranges, and path lengths. In response to the exclusion of visual input, these measures had increased considerably in the patient group. An increased value of a postural sway parameter is not necessarily associated with postural instability (Nardone and Schieppati 2006). Usually, other evidences of postural stability decline are needed. The functional reach (Duncan et al. 1990) is a simple and easily implemented clinical test for postural stability. Results of such testing showed that indeed the anterior margin of stability is markedly reduced in parkinsonians (Schieppati et al. 1994; Smithson et al. 1998; Stack et al. 2005; van Wegen et al. 2001). Jacobs et al. (2006) documented, however, that multiple balance tests including the one-leg stance test, and the gait and pull test items of the UPDRS may provide better assessment of postural stability in subjects with PD than the functional reach test alone.

One of the most intriguing findings which emerged from the present study and which might prove relevant to clinical practice was the effect of vision on the mean COP position observed in both groups, and the excessive forward shift of this position in PD subjects. This finding is in contrast to results of earlier studies, which found that the mean displacement of the center of pressure in parkinsonians was not different from the controls (Burleigh et al. *1995*). Schieppati and Nardone (*1991*) have reported some shifts of the mean (preferred) COP position in PD patients, claiming that the less affected patients are shifted backwards and the more affected patients forwards, with respect to controls. They also found that the COP position correlated with severity of the disease on the Webster scale. Recently, Crenna et al. (*2006*) and Guehl et al. (*2006*) documented postural effects of subthalamic nucleus stimulation on the standing posture in PD patients undergoing deep brain stimulation. They found that therapeutic effect of the stimulation was associated with a significant improvement of the vertical alignment of the trunk and shank, decrease of the hip joint moment, reduction of abnormal tonic and/or rhythmic activity in the thigh and leg muscles and the backward shift of the COP. Our results are consistent with the latter finding. All our PD subjects exhibited forward shift of the mean COP position with the shift magnitude correlating with disease severity. This result has a straightforward explanation. Forward leaning posture is considered as one of the most effective compensatory strategies for improving postural stability in the elderly (Horak et al. *1989*; Blaszczyk et al. *1992*, *1994*). Normal COP position is set to maximize antero-posterior stability range and give the postural system, in the face of perturbation, enough time to complete a recovery program (Blaszczyk et al. *1993*, *1994*). Since the posterior stability border is most corrupted by the ageing process (Blaszczyk et al. *1992*, *1994*) and probably by Parkinson's disease (Horak et al. *2005*), one can expect that the optimal COP position must be forward-shifted. The flexed posture in the elderly and parkinsonians results from just an anterior shift of the mean COP position. This compensatory mechanism has several additional advantages for postural control. Since it increases probability of forward instabilities, it allows a diminution in complexity of typical postural control from "choice reaction" to "simple reaction" form. By reducing the number of recovery strategies or by preselecting one, the elderly (and probably parkinsonians) can implement the balance recovery program much faster.

In the literature, several successful attempts at extracting an informative measure with significant discriminative value for postural stability impairments in patients with Parkinson's disease from spontaneous sway measures are described. Collins and De Luca (*1995*) proposed that the level of muscular stochastic activity across joints controls the stiffness of the musculoskeletal system. In accordance with this hypothesis, Mitchell et al. (*1995*) have documented an increase in stochastic activity in the ML direction in parkinsonians . They argue that this increase in PD patients' mediolateral activity might reflect an attempt to maintain potentially stabilizing movements during quiet standing in the face of impaired movement in the antero-posterior direction. Similarly, Bosek et al. (*2005*) found that both healthy older adults as well as PD patients exhibit higher levels of muscular stochastic activity as compared to younger subjects. In all subjects, eye closure resulted in further increase still in stochastic muscle activity. According to these authors, a postural compensating mechanism is activated under EC conditions and this mechanism is evidently impaired in parkinsonians. Our sway analyses focused on measures that estimate descriptive and summary statistics of the COP that are the most commonly used in clinical practice. We show that measures such as lateral sway indices and mean COP position may be useful adjuncts to evaluate postural stability in patients with Parkinson's disease. It is interesting that the mediolateral sway abnormalities occurred only in PD patients and were absent in elderly controls, a finding which is consistent with other studies (Mitchel et al. 1995; van Wegen et al. 2001; Viitasalo et al. 2002; Rocchi et al. 2006). More importantly, these COP measures correlated with the severity of Parkinson's disease as measured by both the Hoehn-Yahr disability scale and the motor section of the UPDRS. Finally, it should be emphasized that the same sway measures i.e., lateral sway ranges measured under eye open and eye closed conditions were significantly correlated with falls unrelated to freezing.

An increased lateral sway is associated with an increased risk of falling in the elderly (Maki and McIlroy 1996; Maki et al. 1996; Laugthon et al. 2003). Our data showed that the following well-known predictors of a tendency to fall were closely correlated with the amount of lateral sway in PD patients: duration and severity of the disease in addition to gait impairment, postural stability and rigidity. This is in agreement with previous findings (Ashburn et al 2001; Viitasalo et al. 2002). Similar results were found by van Wegen et al. (2001) who studied another stability measure, the ML average time-to-contact which was selectively decreased in PD patients but only in the ML direction, not in the AP direction. All of these findings confirmed the hypothesis that mediolateral sway might be the single best predictor of falling risk in parkinsonians.

It is not surprising that in our study the ML sway measures correlated with Hoehn-Yahr scores and falls unrelated to freezing. Hoehn and Yahr's study of the symptoms and signs of Parkinson's disease introduced the concept of postural instability only at stage 3 in advanced disease (Hoehn and Yahr 1967; Playfer 2001). However, this placement has been challenged by Klawans (1986) who described a tendency to fall at earlier disease stages. Our results confirmed that the deterioration of postural stability control is a continuous process that starts with the onset of the disease, yet efficient compensatory mechanisms obscure the resulting deficits until late stages of the disease when the compounding effects culminate in falls. However, we should also keep in mind that all PD patients were tested ON levodopa and medication side-effects provide additional fall risk factors. (Bloem 1992; Rocchi et al. 2002; Horak et al. 2005). Patients with a good response to levodopa are more likely to suffer falls associated with dyskinesias and motor fluctuations (Ashburn et al. 2001) but these subjects were not included in the present study. That likely explains why sway parameters in our PD patients were additionally increased when compared with the control group. Levodopa increases body sway more in the mediolateral than in the anterior–posterior direction, thus postural stability is worsened in the dopa condition (Roberts-Warrior et al. 2000; Rocchi et al. 2002, 2006).

In conclusion, in Parkinson's disease, at least three spontaneous sway parameters: lateral sway range, sway area and the mean COP position taken together may provide a veridical evaluation for postural instability and associated fall risk. The increase of spontaneous sway indices should be also supplemented with additional measure of stability range such as the functional reach or maximal voluntary leaning.

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References

Ashburn A, Stack E, Pickering RM, Ward CD (2001) A community-dwelling sample of people with Parkinson's disease: characteristics of fallers and non-fallers. Age Ageing 30:47–52
PubMed CrossRef ChemPort

Blaszczyk JW, Lowe DL, Hansen PD (1992) A heuristic model of postural stability. In: Woollacott M, Horak F (eds) Posture and gait: control mechanisms vol. II. University of Oregon Book, Portland, pp 228–231

Blaszczyk JW, Lowe DL, Hansen PD (1993) Age-related changes in the perception of support surface inclination during quiet stance. Gait Posture 1:161–165
CrossRef

Blaszczyk JW, Lowe DL, Hansen PD (1994) Ranges of postural stability and their changes in the elderly. Gait Posture 2:11–17
CrossRef

Bloem BR, Van Dijk JG, Beckley DJ, Roos RAC, Remler MP, Bruyn GW (1992) Altered postural reflexes in Parkinson's disease: a reverse hypothesis. Med Hypotheses 39:243–247
PubMed CrossRef ChemPort

Bosek M, Grzegorzewski B, Kowalczyk A, Lubiński I (2005) Degradation of postural control system as a consequence of Parkinson's disease and ageing. Neurosci Lett 376:215–220
PubMed CrossRef ChemPort

Burleigh A, Horak FB, Nutt J, Frank J (1995) Levodopa reduces muscle tone and lower extremity tremor in Parkinson's disease. Can J Neurol Sci 22:280–285
PubMed ChemPort

Collins JJ, De Luca CJ (1995) The effects of visual input on open-loop and closed-loop postural control mechanisms. Exp Brain Res 103:151–163
PubMed [SpringerLink] ChemPort

Crenna P, Carpinella I, Rabuffetti M, Rizzone M, Lopiano L, Lanotte M, Ferrarin M (2006) Impact of subthalamic nucleus stimulation on the initiation of gait in Parkinson's disease. Exp Brain Res 172:519–32
PubMed [SpringerLink] ChemPort

Duncan PW, Weiner DK, Chandler JM, Studenski SA (1990) Functional reach: a new clinical measure of balance. J Gerontol 45:192–197

Gregoric M, Lavric A (1977) Statokinesimetric analysis of the postural control in parkinsonisms. Agressologie 18:45–48
PubMed

Guehl D, Dehail P, de Seze MP et al (2006) Evolution of postural stability after subthalamic nucleus stimulation in Parkinson's disease: a combined clinical and posturometric study. Exp Brain Res 170:206–215
PubMed [SpringerLink] ChemPort

Hoehn M, Yahr M (1967) Parkinsonism, onset, progression and mortality. Neurology 17:427–442
PubMed ChemPort

Horak FB, Shupert CL, Mirka A (1989) Components of postural dyscontrol in the elderly: a review. Neurobiol Aging 10:727–738
PubMed crossref ChemPort

Horak FB, Nutt JG, Nashner LM (1992) Postural inflexibility in parkinsonian subjects. J Neurol Sci 111:46–58
PubMed crossref ChemPort

Horak FB, Dimitrova D, Nutt JG (2005) Direction-specific postural instability in subjects with Parkinson's disease. Exp Neurol 193:504–521
PubMed crossref

Jacobs JV, Horak FB, Tran VK, Nutt JG (2006) Multiple balance tests improve the assessment of postural stability in subjects with Parkinson's disease. J Neurol Neurosurg Psychiatry 77:322–6
PubMed crossref ChemPort

Kitamura J, Nakagawa H, Linuma K et al (1993) Visual influence on center of contact pressure in advenced Parkinson's disease. Arch Phys Med Rehabil 74:1107–1112
PubMed crossref ChemPort

Klawans HL (1986) Individual manifestations of Parkinson's disease after ten or more years of levodopa. Mov Disord 1:187–192
PubMed crossref ChemPort

Koller WC, Glatt S, Vetere-Overfield B, Hassanein R (1989) Falls and Parkinson's disease. Clin Neuropharmacol 12:98–105
PubMed ChemPort

Lauk M, Chow CC, Lipsitz LA, Mitchell SL, Collins JJ (1999) Assessing muscle stiffness from quiet stance in Parkinson's disease. Muscle Nerve 22:635–639
PubMed crossref ChemPort

Maki BE, McIlroy WE (1996) Postural control in the older adult. Clin Geriatr Med 12:635–658
PubMed ChemPort

Maki BE, Holliday PJ, Topper AKA (1996) Prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. J Gerontol 49:M72–84

Mitchell SL, Collins JJ, DeLuca CJ, Burrows A, Lipsitz LA (1995) Open-loop and close-loop postural control mechanisms in Parkinson's disease: increased mediolateral activity during quiet standing. Neurosci Lett 197:133–136
PubMed crossref ChemPort

Nardone A, Schieppati M (2006) Balance in Parkinson's disease under static and dynamic conditions. Mov Disord 21:1515–20
PubMed crossref

Playfer JR (2001) Falls and Parkinson's disease. Age Ageing 30:3–4
PubMed crossref ChemPort

Raymekers JA, Samson MM, Verhaar HJJ (2005) The assessment of body sway and the choice of the stability parameter(s). Gait Posture 21:48–58
crossref

Roberts-Warrior D, Overby A, Jankovic J, Olson S, Lai EC, Krauss JK, Grossman R (2000) Postural control in Parkinson's disease after unilateral posteroventral pallidotomy. Brain 123:2141–2149
PubMed crossref

Rocchi L, Chiari L, Horak FB (2002) Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease. J Neurol Neurosurg Psychiatry 73:267–274
PubMed crossref ChemPort

Rocchi L, Chiari L, Cappello A, Horak FB (2006) Identification of distinct characteristics of postural sway in Parkinson's disease: a feature selection procedure based on principal component analysis. Neurosci Lett 394:140–145
PubMed crossref ChemPort

Schieppati M, Nardone A (1991) Free and supported stance in Parkinson's disease. Brain 114:1227–1244

Schieppati M, Hugon M, Grasso M, Nardone A, Galante M (1994) The limits of equilibrium in young and elderly normal subjects and in parkinsonians. EEG Clin Neurophysiol 93:286–298

Smithson F, Morris MC, Ganseh R (1998) Performance on clinical tests of balance in Parkinson'sdisase. Phys Ther 78:577–592

Stack E, Ashburn A, Jupp K (2005) Postural instability during reaching tasks in Parkinson's disease. Physiother Res Int 10:146–53

Stolze H, Klebe S, Zechlin C, Baecker C, Friege L, Deuschl G (2004) Falls in frequent neurological diseases—prevalence, risk factors and aetiology. J Neurol 251:79–84

Takagi A, Fujimura E, Suehiro S (1985) A new method of statokinesogram area measurement: application of a statistically calculated ellipse. In: Igarashi S, Black FA (eds) Vestibular, visual control on posture and equilibrium. Karger, Basel, pp 74–79

van Wegen EE, van Emmerik RE, Wagenaar RC, Ellis T (2001) Stability boundaries and lateral postural control in parkinson's disease. Motor Control 5:254–269

Viitasalo MK, Kampman V, Sotaniemi KA, Leppavuori S, Myllyla VV, Korpelainen JT (2002) Analysis of sway in Parkinson's disease using a new inclinometry-based method. Mov Disord 17:663–669

Winter DA (1995) A.B.C. anatomy, biomechanics and control of balance during standing and walking. Waterloo, Ontario, pp. 1–55

Visser M, Marinus J, Bloem BR, Kisjes H, van den Berg BM, van Hilten JJ (2003) Clinical tests for the evaluation of postural instability in patients with Parkinson's disease. Arch Phys Med Rehabil 84:1669–1674