Impairment of postural control is a major problem in patients with Parkinson’s disease, and postural problems become increasingly severe as the disease progresses, despite treatment with levodopa. This increasing severity may reflect the increased involvement of non-dopaminergic pathways, which results in the declining effectiveness of levodopa replacement therapy. There is new hope that an alternative treatment for Parkinson’s disease involving high frequency deep brain stimulation of the subthalamic nucleus or globus pallidus may be more effective than levodopa in improving postural control, presumably because deep brain stimulation also affects non-dopaminergic pathways.

Most studies that have examined the effectiveness of levodopa and deep brain stimulation in treating the motor control problems of Parkinson’s disease, such as postural instability, have used clinical rating scales, for example the unified Parkinson’s disease rating scale (UPDRS). Such measures of postural control are not designed to differentiate among automatic postural control may involve basal ganglia circuits distinct from those controlling voluntary postural movement; for example, levodopa is more effective at improving postural control resulting from deep brain stimulation and levodopa, and their interaction, and to determine whether quantitative changes in postural sway caused by treatment are reflected in changes in UPDRS measures of postural control.

Few studies have quantified postural stability during quiet stance in subjects with Parkinson’s disease. In those that did, the results were often contradictory and limited. Some studies did not find abnormalities, while others found less postural sway in subjects with Parkinson’s disease than in aged matched control subjects. Such discrepancies may be explained by differences in research design: subject populations in different studies had different severities of Parkinson’s disease, and some subject populations were on levodopa while others were off. In only one study was the effect of levodopa treatment on postural sway examined, and in that study only the anteroposterior direction was considered; a change in sway velocity was found but not in sway area. However, another study suggested that, when on levodopa, subjects with Parkinson’s disease have more difficulty in controlling lateral postural sway than anteroposterior sway. Studies have also suggested that increased lateral sway is associated with an increased risk of falling in elderly subjects.

The results of previous studies in our laboratory suggest that automatic postural control may involve basal ganglia circuits distinct from those controlling voluntary postural movement; for example, levodopa is more effective at improving postural control resulting from deep brain stimulation and levodopa, and their interaction, and to determine whether quantitative changes in postural sway caused by treatment are reflected in changes in UPDRS measures of postural control.
voluntary postural movements—such as step initiation and rise to toes—than automatic postural responses to external perturbations.\(^{15}\) Because levodopa is more effective for voluntary than for automatic postural control in subjects with Parkinson’s disease, we hypothesised the following:

- that levodopa is not effective in improving control of quiet stance;
- that deep brain stimulation is more effective than levodopa for automatic postural control\(^{17}\) because deep brain stimulation affects both dopaminergic and non-dopaminergic pathways;
- that the interaction of deep brain stimulation with levodopa results in improved postural stability.

**METHODS**

**Subjects**

Six subjects with Parkinson’s disease and 11 healthy control subjects gave informed consent before inclusion in this study, approved by the human subject committee of Good Samaritan Hospital, Portland, Oregon.

Control subjects were physically active and without musculoskeletal or neurological disorders. Their mean (SD) age was 64 (6.4) years (range 54 to 74 years). The mean age of the subjects with Parkinson’s disease was 61 (9.1) years (range 48 to 75 years), and the duration of their disease, 16 (5.4) years (range 8 to 21 years). All subjects with Parkinson’s disease could stand independently and were responsive to levodopa. Medical examination and history showed they did not have other pathological conditions that could affect postural control.

Table 1 presents ages, duration of Parkinson’s disease, total motor UPDRS scores, clinical dyskinesia scores, and drugs taken. All subjects with Parkinson’s disease were scored 2.5–5 in the Hoehn and Yahr scales, depending on treatment condition.

The patients with Parkinson’s disease were a subset of subjects from a randomised double blinded clinical study investigating deep brain stimulation in the subthalamic nucleus or globus pallidus (see Burchiel et al for details of surgery and optimisation of stimulation parameters\(^{16}\)). During surgery bilateral electrodes were implanted either in the subthalamic nucleus or in the globus pallidus under local anaesthesia. Subjects with electrodes implanted bilaterally in the subthalamic nucleus or globus pallidus were not differentiated in this study because the small number of subjects did not allow comparative analyses.

Subjects with Parkinson’s disease were tested six months after surgery to allow the effects of deep brain stimulation to stabilise.\(^{19}\) They were tested under four treatment conditions:

- Baseline (that is, off levodopa and off stimulation (off condition));
- Only deep brain stimulation (dbs condition);
- Only drug treatment (dopa condition);
- Both deep brain stimulation and levodopa (dbs + dopa condition).

The off condition was obtained by a dopamine washout of at least 12 hours and shutting the stimulator off 20 minutes before tests. The subjects were considered off or on treatment by clinical signs including change in the UPDRS, 0–10 self rating scale, and minimal dyskinesia. Conditions were tested in the following order: (1) (approximately 40 minutes after turning stimulators on); (2) (approximately 60 minutes after administration of optimised dopamine treatment); (3) (approximately 40 minutes after turning stimulators on); (4) (approximately 60 minutes after administration of optimised dopamine treatment).

**Static posturography**

To measure postural sway, subjects stood on a dual force plate platform, with one foot on each force plate, for three sequential trials. Subjects were instructed to maintain an upright standing position, with arms at their sides, eyes open with gaze straight ahead at an art poster, and feet shoulder width apart. Four vertical forces were recorded from each force plate at 480 Hz for 60 seconds, and data were filtered by a 30th order low pass FIR digital filter (cut off frequency 10 Hz) and downsampled at 20 Hz. The centre of foot pressure (CoP) of each foot (CoP\(_{\text{left}}\) and CoP\(_{\text{right}}\)) and the total body CoP were computed from the vertical forces. The CoP is the point location of the ground reaction force vector\(^{20}\) and reflects the sway of the body (biological noise) and forces used to maintain the centre of gravity within the support base.\(^{21}\)

**CoP postural sway variables**

Three uncorrelated CoP variables characterised postural steadiness\(^{25}\): (1) root mean square distance (rms), which quantifies the CoP variability around the mean CoP trajectory; (2) mean velocity of CoP displacement; and (3) 95% power frequency (f\(_{95}\)), which represents the frequency below which 95% of the total power is found. These variables were computed for the bidimensional CoP trajectory (both the anteroposterior and mediolateral directions of total body CoP displacement), and for individual foot CoP displacements. In addition, a 95% confidence ellipse for each trial was estimated,\(^{25}\) which encloses approximately 95% of the points on the CoP trajectory. The area of the confidence ellipse

### Table 1 Demographic and clinical data of subjects with Parkinson’s disease

<table>
<thead>
<tr>
<th>Subject</th>
<th>DBS site</th>
<th>Age (years)</th>
<th>PD duration (years)</th>
<th>UPDRS</th>
<th>Dyskinesia scores</th>
<th>Anti-PD drugs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (^{(1)})</td>
<td>STN</td>
<td>61</td>
<td>18</td>
<td>OFF</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>II</td>
<td>GPi</td>
<td>48</td>
<td>11</td>
<td>DBS</td>
<td>40</td>
<td>30.5</td>
</tr>
<tr>
<td>III</td>
<td>STN</td>
<td>53</td>
<td>21</td>
<td>DOPA</td>
<td>65</td>
<td>25.5</td>
</tr>
<tr>
<td>IV</td>
<td>GPi</td>
<td>75</td>
<td>8</td>
<td>DOPA</td>
<td>40</td>
<td>26.5</td>
</tr>
<tr>
<td>V</td>
<td>GPi</td>
<td>61</td>
<td>12</td>
<td>DOPA</td>
<td>21.5</td>
<td>10</td>
</tr>
<tr>
<td>VI</td>
<td>STN</td>
<td>69</td>
<td>19</td>
<td>DOPA</td>
<td>78</td>
<td>50</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Dyskinesia scores collected one year after surgery instead of six months.

DBS, deep brain stimulation; DOPA, dopamine treatment; GPi, globus pallidus internus; OFF, no treatment; STN, subthalamic nucleus.
and the direction of maximum sway (mdir) were quantified.

Comparisons of CoP variables under each foot allowed measures of postural symmetry. Postural symmetry was examined using the absolute symmetry index. If $P_{\text{left}}$ and $P_{\text{right}}$ are values of a parameter extracted from CoP$_{\text{left}}$ and CoP$_{\text{right}}$, the absolute symmetry index (ASIp) for this parameter is defined as:

$$\text{ASIp} = \frac{2 \cdot (P_{\text{left}} - P_{\text{right}})}{P_{\text{left}} + P_{\text{right}}} \times 100$$

**Statistical analysis**

The non-parametric Wilcoxon signed-rank test compared UPDRS motor scores and differences among sway parameters in subjects with Parkinson's disease under the four conditions. Analysis of variance (ANOVA) (repeated measures) compared variables between control subjects and subjects with Parkinson's disease. Correlation analysis between CoP and UPDRS subscores was performed across all four conditions with the non-parametric Spearman's rank method.

**RESULTS**

**Clinical scores**

Results from the UPDRS motor examination for each condition are represented in fig 1. In the off condition, the mean UPDRS motor score was largest (worst clinical signs), and the standard deviation was also largest. The UPDRS score was significantly reduced in the dbs and dopa conditions. The decrease was larger in the dopa condition than in the dbs condition. In the dbs+dopa condition, UPDRS scores were further reduced compared with the dopa and dbs conditions. The variability also decreased under treatment, especially in the dopa condition.

**General characteristics of postural sway**

The CoP trajectory of a representative control subject is illustrated in fig 2. Postural sway displacement of control subjects was larger in the anteroposterior than in the mediolateral direction.

In fig 3, CoP trajectories are shown during each condition for a representative subject with Parkinson's disease. Both Parkinson's disease and the different treatment conditions significantly affected postural sway. In the off condition (fig 3A), although the range of CoP displacement was apparently similar to the control subject in fig 2, its shape was quite different, with frequent changes of direction. On the other hand, in the dbs condition (fig 3B), postural sway looked normal in shape and even slightly smaller than normal in range. In the dopa condition (fig 3C), the main features of the CoP trajectory changed. The CoP trajectory covered a larger area with a larger than normal range of sway especially in the mediolateral direction, in which it was almost as large as in the anteroposterior direction. Postural sway in the dbs+dopa condition (fig 3D) was more similar to the postural sway in the dopa condition than in the dbs condition.

**Measures of postural stability in standing**

Group means of total body CoP variables are summarised in fig 4 for rms, mean velocity, and $f_{95}$. In the off condition, subjects with Parkinson's disease showed larger rms (fig 4A) than control subjects. Deep brain stimulation reduced rms ($p < 0.05$) to within normal limits. The intersubject variability of rms was also significantly reduced in the dbs condition compared with the off condition. Conversely, dopamine increased rms of CoP displacement, making it more than twice the value of control subjects ($p < 0.01$). In the dopa condition rms was also significantly larger than in the dbs condition.

![Figure 1](https://example.com/f1.png)

**Figure 1** Mean values of the UPDRS motor subscale (range 0–108) in subjects with Parkinson’s disease in the four conditions. DBS, under deep brain stimulation only; DBS+DOPA, under deep brain stimulation and levodopa; DOPA, under levodopa only; OFF, no treatment; UPDRS, unified Parkinson’s disease rating scale. Error bars = SD. *$p < 0.05$.

![Figure 2](https://example.com/f2.png)

**Figure 2** Centre of foot pressure (CoP) trajectory of a representative control subject. Left: Monodimensional time series in mediolateral (ML) and anteroposterior (AP) directions, obtained from total body CoP. Right: Bidimensional displacement of CoP sway in the horizontal plane of each single foot and of the total body (centre). For simplicity, the time series are normalised to their mean value.
In the **dbs+dopa** condition, **rms** remained high and almost unchanged compared with the **off** condition.

Mean velocity of CoP displacement (fig 4B) was also strongly affected by Parkinson’s disease and the **dopa** and **dbs** conditions. The largest mean velocity occurred in the **off** condition, in which it was about eight times the control subjects’ values (p < 0.05). This large mean velocity reflects the long sway path travelled over 30 seconds by subjects with Parkinson’s disease. In all treatment conditions, mean velocity was decreased compared with the **off** condition, even if statistical significance was only approached because of the large intersubject variability in the **off** condition. However, in the **dbs** condition, mean velocity of subjects with Parkinson’s disease was very close to mean velocity of control subjects (p > 0.05),

![Figure 3](image)

**Figure 3** Centre of foot pressure (CoP) trajectories in the horizontal plane of a representative subject with Parkinson’s disease in the four test conditions (panels A to D). For simplicity, the time series are normalised to their mean value. DBS, under deep brain stimulation only; DBS+DOPA, under deep brain stimulation and levodopa; DOPA, under levodopa only; OFF, no treatment.

![Figure 4](image)

**Figure 4** Variables extracted from bidimensional centre of foot pressure (CoP) excursions. (A) Root mean square (rms) of distance of CoP from the centre of sway. (B) Mean velocity (MV) of CoP trajectory. (C) Frequency below which lie the 95% of the total power (f95%). For each variable, bars represent means and the error bars, 1 SD. Control subjects are represented by shaded bars, subjects with Parkinson’s disease by empty bars. DBS, under deep brain stimulation only; DBS+DOPA, under deep brain stimulation and levodopa; DOPA, under levodopa only; OFF, no treatment. *p < 0.05; **p < 0.01.
was significantly different from normal values (p < 0.01). In the mediolateral direction (mean value 38.6°), which was normal (p < 0.01), as illustrated in fig 5, and mdir shifted toward the mediolateral direction. In the dbs+dopa condition, postural sway was reduced in the mediolateral direction, and mdir moved toward the anteroposterior direction compared with the dopa condition. Nevertheless, the CoP ellipse values for subjects with Parkinson's disease in the dbs+dopa condition remained different from control subjects.

Postural asymmetry

A surprising degree of asymmetry in postural control between the feet during stance was observed in the elderly control subjects (table 3). The rms asymmetry in subjects with Parkinson's disease across the four conditions was never much higher than for control subjects (with the highest values in the off condition and the lowest values in the dbs condition; table 3). These results suggest that neither Parkinson's disease nor treatment conditions significantly affected the difference in size of the left and right CoP displacement.

In contrast, the mean velocity and \( f_{95\%} \) were significantly more asymmetrical in subjects with Parkinson's disease (off condition) than in control subjects, indicating the dominance of one extremity in controlling the velocity and frequency of postural sway. This asymmetry was brought back to normal values by deep brain stimulation, probably owing to the bilateral nature of electrical stimulation. Results in the dbs and Dopa columns are presented in table 2.

### Table 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Area (mm²)</th>
<th>MDir (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Controls</td>
<td>484</td>
<td>197 to 998</td>
</tr>
<tr>
<td>OFF</td>
<td>1044</td>
<td>290 to 2947</td>
</tr>
<tr>
<td>DBS</td>
<td>246</td>
<td>72 to 685</td>
</tr>
<tr>
<td>Dopa</td>
<td>2157</td>
<td>1138 to 4075</td>
</tr>
<tr>
<td>DBS+Dopa</td>
<td>1179</td>
<td>287 to 3907</td>
</tr>
</tbody>
</table>

\( ^{a}p<0.05 \) v Controls; \( ^{b}p<0.01 \) v Controls; \( ^{c}p<0.05 \) v DBS; \( ^{d}p<0.01 \) v DBS; \( ^{e}p=0.05 \) v DBS; \( ^{f}p=0.01 \) v DBS; \( ^{g}p<0.05 \) v OFF; \( ^{h}p<0.01 \) v OFF; \( ^{i}p=0.01 \) v DBS; \( ^{j}p=0.05 \) v DBS.
needed by these patients to stabilise posture in stance.

interpreted as the large amount of neural control activity
significantly correlated with resting tremor in the UPDRS,
\( p = 0.024 \)

with

(items 26–31;

ation score (

Power spectral

were probably related to postural tremor as well as to the short

mal frequencies of sway in subjects with Parkinson's disease
joints in stance and show larger background EMG activity and
Parkinson's disease have higher passive stiffness of ankle
joints may be responsible for rapid, jerky CoP movements and

frequent adjustments of the CoP trajectory characteristic of

CoP variable.

Correlation with clinical scores

Spearman’s rank correlation coefficients indicated that the
only CoP based postural variable that significantly correlated
with the UPDRS or its components was \( f_{95\%} \). The \( f_{95\%} \) value cor-
related significantly with the global UPDRS motor examination
score \( (r = 0.43; p = 0.04) \) and with overall severity of
posture-tremor \( (r = 0.49; p = 0.016) \), in particular,

with gait (item 29, \( r = 0.60; p = 0.003 \)), bradykinnesia (item 31,
\( r = 0.60, p = 0.003 \)), and tremor (items 20–21, \( r = 0.56,
 p = 0.024 \)). The high correlations between \( f_{95\%} \) and these com-
ponents of UPDRS suggest that poor performance in axial
motor tasks is associated with an increase in postural sway
frequency. Interestingly, the posture component (item 28) and
the postural stability (pull test; item 30) component of the
UPDRS did not correlate with \( f_{95\%} \) or with another quantitative
CoP variable.

DISCUSSION

In this study we found that subjects with Parkinson’s disease
have abnormal postural sway in stance and that treatment
with levodopa increases postural sway abnormalities, whereas
treatment with deep brain stimulation improves postural
sway. The differences in quantitative CoP measures between
control subjects and subjects with Parkinson’s disease in the of
condition illustrate the way in which neural postural control
of stance is affected by Parkinson’s disease when no therapeu-
tic intervention is provided. The high mean velocity of sway for
subjects with Parkinson’s disease in the of condition can be
interpreted as the large amount of neural control activity
needed by these patients to stabilise posture in stance."
Deep brain stimulation appears to be effective in stabilising stance, as indicated by the variables extracted from static posturography, which were all very close to normal values in the deep brain stimulation condition. These results suggest that non-dopaminergic pathways, such as those from the basal ganglia to brain stem centres, are probably involved in postural control. The effectiveness of deep brain stimulation, but not levodopa, in reducing postural sway is supported by studies showing that the former improved axial UPDRS measures and limb measures, but the latter did not improve axial measures. The action of deep brain stimulation may help integrate information from the proprioceptive system, improving kinaesthetic control of the centre of mass.

In the "dbs+t-dopa" condition, deep brain stimulation attenuated the negative effects on postural sway that levodopa introduced. In particular, mediolateral oscillation was reduced, suggesting more trunk stability. Nevertheless, the large sway area in the "dbs+t-dopa" condition showed that improved postural control caused by deep brain stimulation was not enough to compensate for the reduced stiffness of muscle and joints caused by levodopa. This linear summation of the effects from levodopa and deep brain stimulation has been observed previously in studies of changes in UPDRS measures, especially with globus pallidus stimulation. The asymmetrical nature of Parkinson’s disease was reflected in postural sway variables extracted from each foot. For subjects with Parkinson’s disease, results showed a large asymmetry for CoP mean velocity and f95%, but normal symmetry for rms. Thus the variables related more to neural control activity (mean velocity and f95%) present more differences between the feet in subjects with Parkinson’s disease than the variable related to achievement of postural stability (rms), suggesting that symmetrical balance can be achieved through asymmetrical neural control activity. The improved symmetry of postural control between the legs in the "dbs+t-dopa" condition also suggests that bilateral stimulation in the globus pallidus or subthalamic nucleus can normalise bilateral involvement of the legs for posture. In contrast, levodopa worsened asymmetry of postural control, perhaps because it decreased stiffness without improving postural control, thus revealing the underlying asymmetry.

The correlation analysis between each quantitative postural sway measure and the UPDRS motor examination showed that only f95% of the CoP was significantly correlated with the UPDRS total score and the tremor and posture+gait subcomponents. The positive correlation between f95% and clinical tremor measures showed that tremor influences postural stability and can be detected by static posturography. Even small amounts of tremor may be transmitted to forces at the ground and can therefore influence initiation and control of postural movements. The high correlation of f95% with the "posture+gait" item primarily came from correlations with posture, gait, and bradykinesia (items 28, 29, and 31). The significant correlations with gait and bradykinesia suggest that difficulties and slowness in motion can be paradoxically accompanied by high frequency components in body sway. In fact, the necessity for frequent neural control over the CoP displacement, rather than tremor per se, may be the cause of the difficulties and slowness in motion asymmetrical in patients with Parkinson’s disease. Poor correlations among the UPDRS scores, rms, and mean velocity suggest that UPDRS predicts sway area and velocity poorly.

Conclusions

Although correlations between UPDRS and sway variables may have been low in this study owing to the small number of subjects, clinicians might find it useful to measure the sway path, as rms has been related to the effectiveness of the postural control system, and mean velocity of sway has been related to the amount of postural regulatory activity. Results from this preliminary study suggest that quantitative evaluation of static posturography is sensitive to Parkinson’s disease and to treatments with levodopa and deep brain stimulation, and such evaluation may become a useful adjunct to clinical measures of motor control in patients with Parkinson’s disease.

ACKNOWLEDGEMENTS

This research was supported by NIH grants AG 40812 and AG 06457. We thank Dr K Burchiel and Dr V Anderson for patient referrals, Professor A Cappello for helpful reviewing, and A Gross for help with data collection.

Authors’ affiliations

L Rocchi, L Chiori, Department of Electronics, Computer Science and Systems, University of Bologna, Bologna, Italy
F B Horak, Neurological Sciences Institute, Oregon Health & Science University, Beaverton, Oregon, USA

Competing interests: none declared.

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