Proprioceptive control of wrist movements in Parkinson’s disease
Reduced muscle vibration-induced errors

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Summary
The effects upon the trajectories of practised slow (~9°/s) voluntary wrist-extension movements of applying vibration to the tendon of an antagonist muscle (flexor carpi radialis) during the course of the movement have been studied in patients with idiopathic Parkinson’s disease and age-matched healthy individuals. In both patient and control groups, flexor vibration elicited undershooting of wrist-extension movements. Wrist extensor and flexor surface EMG recordings indicated that, in patients and controls, such undershooting resulted principally from sustained reductions in extensor (prime mover) activity. Small vibration reflexes were commonly elicited in the wrist flexors which, in both Parkinson’s disease and healthy subjects, were usually otherwise virtually quiescent during these slow extension movements. The amplitudes of such vibration reflexes did not differ systematically between patient and control groups and appeared inadequate to have exerted an appreciable braking action upon the extension trajectories. However, the extent of vibration-induced undershooting was, on average, significantly less in the Parkinson’s disease group. In a subgroup of patients with asymmetrical parkinsonism the effects of antagonist vibration upon wrist movements of the more and less affected limb were compared. The degree of vibration-induced undershooting was significantly smaller on the more affected side. This finding suggests that disturbed proprioceptive guidance of voluntary movements in Parkinson’s disease is related to the severity of clinical motor deficits. A small number Parkinson’s disease patients were studied ‘ON’ and ‘OFF’ their routine anti-parkinsonian medication. A non-significant tendency was found for vibration-induced errors to be less marked in the ‘OFF’ state. In a separate series of experiments, under isometric conditions, vibration-induced EMG changes were recorded whilst subjects attempted to maintain a steady (15% maximum) voluntary wrist extensor effort. Results in control subjects suggested that prolonged flexor vibration produced otherwise virtually quiescent during these slow extension movements. The amplitudes of such vibration reflexes did not differ systematically between patient and control groups and appeared inadequate to have exerted an appreciable braking action upon the extension trajectories. However, the extent of vibration-induced undershooting was, on average, significantly less in the Parkinson’s disease group. In a subgroup of patients with asymmetrical parkinsonism the effects of antagonist vibration upon wrist movements of

Keywords: Parkinson’s disease; proprioception; vibration; voluntary movement

Abbreviations: MPTP = N-methyl-4-phenyl-1,2,3,6-tetrahydropyridine; NV = non-vibrated condition (absence of flexor tendon vibration); V = vibrated condition (presence of flexor tendon vibration)

Introduction
Experimental evidence from studies upon parkinsonian patients indicates that both reflex and voluntary motor responses following proprioceptive input are abnormal in human basal ganglia disease. It has long been established that the later components of stretch reflexes are pathologically enhanced in Parkinson’s disease (Tatton and Lee, 1975; Mortimer and Webster, 1979; Cody et al., 1986). Subsequently, Moore (1987) has reported that parkinsonian patients with asymmetrical disease overestimate the trajectory of the more bradykinetic limb when attempting to match slow, active movements of the two arms. This observation suggests that a disturbance of proprioceptive guidance
exists in Parkinson’s disease which may reflect a mismatching of proprioceptive feedback and corollary discharge. A possible neuronal basis for impaired proprioceptive integration in Parkinson’s disease has been provided by recordings of the patterns of unitary discharge from the basal ganglia of primates rendered parkinsonian by treatment with N-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP). Pallidal neurons of MPTP-treated primates have been found to show increased responsiveness and reduced selectivity of response to peripheral inputs, e.g. modulation by movements at several joints rather than a single one and a loss of directional specificity (DeLong et al., 1985; Filion et al., 1988).

In the present experiments we have used muscle vibration to investigate whether proprioceptive guidance of slow voluntary wrist movements is abnormal in Parkinson’s disease. Vibration is a powerful stimulant of muscle receptors and particularly spindle primary endings in man (Burke et al., 1976a; b; Roll and Vedel, 1982) and provides a means of artificially activating proprioceptors during voluntary movements. Vibration, when combined with joint movement, elicits quantitatively erroneous proprioceptive messages concerning movement parameters (Roll et al., 1989), therefore forms an experimental method of misinforming the CNS of actual kinematics. Such stimulation has been shown in healthy individuals to induce kinaesthetic illusions (Goodwin et al., 1972a) and alterations of voluntary movement trajectories (Capaday and Cooke, 1981; Cody et al., 1990). Thus, comparison of the form of vibration-induced movement errors in parkinsonian and control subjects provides a method of assessing whether central neural utilization of proprioceptive feedback in regulating motor activity is deranged in Parkinson’s disease.

Our finding that antagonist vibration elicits an undershooting of slow wrist movements in parkinsonian patients, as occurs in healthy individuals, suggests that proprioceptive input is used in a qualitatively normal manner in continuously regulating voluntary motor output in Parkinson’s disease. However, the fact that the extent of vibration-induced movement errors was reduced in the parkinsonian group supports the existence of a quantitative impairment of proprioceptive guidance in Parkinson’s disease.

Methods

Subjects

Twenty-nine Parkinson’s disease patients (17 male, 12 female) and 23 healthy subjects (11 male, 12 female) were studied. The mean age (±SD) of the parkinsonian group was 65.5 ± 8.8 years, and that of the control group was 62.6 ± 12.5 years; the ages of the two groups did not differ significantly (P > 0.3, t test). A diagnosis of idiopathic Parkinson’s disease was established in each of the patients according to the criteria of Hughes et al. (1992) and signs and symptoms were graded according to the classifications of Hoehn and Yahr (1967) and Webster (1968). When comparing control subjects and Parkinson’s disease patients, the patients were studied in their more parkinsonian state, i.e. the more severely affected limb was studied in hemiparkinsonism and the ‘OFF’ state in patients able to forgo medication for 12 h. The clinical details of the parkinsonian subjects are given in Table 1. All subjects participated with their informed consent and the protocols were approved by the Central Manchester Health Authority Research Ethics committee.

Experimental arrangement

Subjects were seated and grasped the vertical handle of a manipulandum. The forearm was semi-pronated and rested on a horizontal support of foam padding. Its distal end was clamped by padded bars leaving the wrist free to make angular extension and flexion movements of the handle in a horizontal plane. The manipulandum handle was attached to a shaft pivoted directly below the wrist joint and linked by low friction bearings to a pulley system. Weights were suspended from the pulley so that subjects made wrist-extension movements against a load corresponding to ~15% of their individual maximum contraction strength. Calibration measurements using a strain ring coupled to the handle of the manipulandum indicated that the torque acting at the handle remained constant throughout the range of wrist angles investigated. A precision potentiometer incorporated in the manipulandum provided an analogue signal of wrist angle.

Voluntary wrist-extension movements were studied. The required trajectory was a steady (ramp) extension of velocity 8.9°/s from a starting point at which the wrist was at the anatomically neutral position (carpus aligned with axis of forearm). A mechanical stop was located on the manipulandum to ensure that subjects commenced extension movements from a uniform wrist angle. Subjects were denied direct vision of the manipulandum, their forearm and hand by a screen. Subjects viewed a VDU screen placed at eye-level and ~1 m in front of them. The room was darkened. Initially, during the practice trials, two cursors were displayed; one (target cursor) was generated by a computer and indicated the target trajectory as it moved horizontally across the screen whilst the other (movement cursor) signalled the subjects’ own wrist movements. During the initial practice period the subject’s task was to superimpose the two cursors as they both traversed the screen (sweep time 2.25 s). A warning auditory cue sounded 1 s before the sweep started. Trials were separated by an interval of 5 s which allowed subjects adequate time to return the manipulandum to the desired starting position prior to the next trial. Subjects were given sufficient practice trials (typically 15) for them to attain a good degree of reproducibility of movement performance.

During the main experimental trials the movement cursor was extinguished but the target cursor continued to be displayed to provide subjects with a timing cue and the auditory warning prompt was retained. Thus, subjects were now required to reproduce the practised movement profile
Vibration-induced movement errors in Parkinson’s disease

Table 1 Clinical details of the Parkinson’s disease patients in this study

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Disease duration (years)</th>
<th>Clinical gradings</th>
<th>Treatment</th>
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<td>8 (II)</td>
<td>LD; AC; Amant.</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Amant.</td>
</tr>
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<tr>
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<tr>
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<td>12 (III)</td>
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<tr>
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<td>LD; Se.</td>
</tr>
<tr>
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<td>59</td>
<td>F</td>
<td>8</td>
<td>18 (IV)</td>
<td>LD; Amant.; Se.</td>
</tr>
</tbody>
</table>

The two values listed under clinical gradings refer to the Webster (1968) Parkinson’s disease rating scale which provides an overall index of disease severity with a range of 0–30 and, in parentheses, the Hoehn and Yaehr (1967) staging scale with a range of I–IV. Medication abbreviations: LD = l-dopa; Se = seleginine; Amant = amantidine; DA = dopamine agonist; AC = anti-cholinergic.

accurately, in the absence of visual feedback of movement performance and under exclusively proprioceptive guidance. Voluntary wrist-extension movements were made either in the absence (non-vibrated, NV) or presence (vibrated, V) of flexor tendon vibration.

**Antagonist muscle vibration**

High frequency (100 Hz) sinusoidal mechanical stimuli were applied transcutaneously to the tendon of the flexor carpi radialis muscle using a small electromagnetic vibrator suspended from a frame and counterweighted to press on the tendon with a constant force of 2.5 N (see Cody et al., 1986). A length transducer incorporated in the vibrator was used to monitor the stimulus waveform. The peak-to-peak amplitude of the vibration was set at 0.7 mm. Palpation over several muscles in the flexor and extensor compartments confirmed that the flexor carpi radialis muscle was by far the most powerfully stimulated and that there was no inadvertent spread of vibration to extensor muscles. The head of the vibrator probe (1×1.5 cm) was left in place throughout the experiment but the device was only activated during V trials.

In V trials stimulation commenced 250 ms after the onset of the tracking task and lasted throughout the remaining 2000-ms movement time.

**Electromyography**

EMGs were recorded from the extensor and flexor compartments of the forearm using two pairs of surface disc electrodes positioned over the bellies of extensor carpi ulnaris and flexor carpi radialis, respectively. EMG signals were amplified and bandpass filtered (20 Hz to 3 kHz).

**Experimental protocol**

Each subject performed a series (24–40 trials) of wrist-extension movements in which an equal number of NV and V trials were interspersed in a pseudorandom manner. In Parkinson’s disease patients whose signs were symmetrical, the wrist of the preferred hand was routinely tested. In powerfully stimulated and that there was no inadvertent spread of vibration to extensor muscles. The head of the vibrator probe (1×1.5 cm) was left in place throughout the experiment but the device was only activated during V trials.

In V trials stimulation commenced 250 ms after the onset of the tracking task and lasted throughout the remaining 2000-ms movement time.
impractical to study both sides. A number of patients (n = 10) were investigated both ‘OFF’ L-dopa medication (12 h unmedicated) and ‘ON’ it (i.e. 1 h after a routine dose of L-dopa, sufficient to produce unequivocal clinical improvement). Recordings from the control group were matched with those of the parkinsonian group with respect to handedness.

Vibration-evoked reflexes
A separate series of control experiments was carried out to record the reflexes evoked in the wrist extensor and flexor muscles by prolonged (2-s) periods of vibration of the tendon of the flexor carpi radialis. This was done to allow an assessment of the possible contribution of such reflexes to the vibration-induced alterations in movement trajectories observed in the main set of experiments.

Seven healthy subjects (aged 20–68 years) and three Parkinson’s disease patients (aged 56–78 years) were studied. (The controls and two of these three patients did not participate in the main series of experiments.) In the vibration-evoked reflex experiments, the patients were examined in the period before a dose of L-dopa was due. At the time of the experiment the overall Webster ratings of these three patients were 10, 12 and 15, and their respective Hoehn and Yahr (1967) stagings were II, II and III. The right hand was studied in all cases; this corresponded to the dominant hand in all controls and two of the three patients.

In order to attempt to eliminate confounding changes in voluntary drive, recordings were made under isometric conditions. The manipulandum was fixed and coupled to a force transducer. At the beginning of each trial, subjects were required to exert a wrist extensor force of 15% of their individual maximum, aided by a visual monitor of their contraction strength. They were then asked to maintain the same level of voluntary effort, with eyes closed, throughout the remainder of the trial (~2.5 s). EMG recordings were made in a similar manner to those made in the main series. Trains of vibration, of 2 s duration and similar frequency and amplitude to the main series, were applied to the tendon of the flexor carpi radialis, commencing once the subject had attained the target force and closed his eyes. After each trial, subjects relaxed. Each subject performed a series of trials (typically 25) at ~30-s intervals.

Data analysis and statistics
In the main series, simultaneous averages (n = 12–20) of movement trajectories and extensor and flexor rectified EMGs, from V or NV trials, were made using a Dell 333SL PC (Limerick, Eire) running Asyst software, stored on hard disc and plotted on a X–Y recorder. Averages were routinely made off-line from data previously recorded on a digital taperecorder. The amplitudes of averaged wrist-extension trajectories were regularly measured at 1.65 s after the beginning of the movement (see Figs 1 and 2). Amplitude measurements from the averages of V and NV sets of trials of individual subjects were used to calculate corresponding V:NV amplitude ratios. Conventional parametric statistics were used to determine mean (and SD) values. Comparisons of movement amplitudes, which did not differ significantly from normal distributions (F test, P > 0.05), within subject groups were made using paired t tests and those between groups were made using unpaired t tests. The V:NV ratios were compared using non-parametric tests; Wilcoxon’s matched pairs signed rank test was applied for within-group
Vibration-induced movement errors in Parkinson’s disease

Results

Vibration-induced alterations of movement trajectories in healthy subjects

Application of vibration to the tendon of the flexor carpi radialis muscle throughout the course of practised slow wrist-extension movements consistently elicited a marked reduction in the amplitude of the movements, made by healthy subjects at measurement time (1.65 s after the ‘go’ cue).

Figure 1A shows the averaged \((n = 12)\) trajectories of wrist-extension movements, and the associated extensor and flexor rectified EMG patterns, of a representative control subject made in the presence and absence of flexor carpi radialis vibration. Antagonist vibration produced an undershooting of the target trajectory and a reduction in movement speed. The amplitudes of the averaged NV and V extension trajectories at the measurement time were 17.25° and 11.75°, respectively; thus, antagonist vibration resulted in a reduction in movement amplitude of just over 30% in this subject.

The EMG records indicate that the subject produced these slow wrist-extension movements, both in the absence and presence of vibration, by smoothly increasing activation of the extensor muscles with almost no co-contraction of the flexors, as did most others. The progressive increase in extensor EMG which accompanied extension movements does not appear to have been due to a need for subjects to increase the absolute force of their contractions since the mean amplitude of V movements was 69% of that of NV movements. Statistical analysis indicated that extension

cited throughout. Force records were not analysed, since vibration artifacts were often present.

In the control experiments investigating vibration-evoked reflexes, averaged (typically 25 trials), rectified, EMG responses were computed (Sigavg software, CED Ltd, Cambridge, UK) on-line. Measurements of the mean levels of extensor EMG, occurring over 50-ms epochs, were made (i) prior to onset of vibration, (ii) at 1.65 s following onset of vibration and (iii) 0.4 s following termination of vibration. These EMG measurements were used to evaluate, respectively, (i) background level, (ii) activity at a time corresponding to measurement time for movement trajectories in the main series and (iii) level of voluntary effort after any reflex effects had subsided. Within-subject comparisons of EMG levels (relative to background) at these times were made using paired \(t\) tests. Two-tailed \(P\) values are routinely compared and the Mann–Whitney \(U\) test for between-group comparisons.

Comparison of the EMG patterns of the V trajectories with their NV counterparts indicates that the vibration-induced reduction in movement speed was associated with a more gradual build-up of extensor activity. In some trials small reflex phasic increases in flexor activity were noted, commencing shortly after the onset of vibration.

Figure 1B shows the mean (+ SD) wrist-extension amplitudes of the control group made during NV and V trials. The mean amplitude of V movements was 69% of that of the NV movements. Statistical analysis indicated that extension
movements made in the presence of vibration were signifi-
cantly smaller than those made in the absence of vibration
\( (P < 0.001, \text{ paired } t \text{-test}) \).

**Vibration-induced alterations of movement trajectories in Parkinson’s disease patients**

Antagonist vibration elicited a qualitatively similar alteration
of wrist-extension trajectories in Parkinson’s disease patients
to that observed in control subjects, namely, a reduction in
the amplitude of movement and undershooting of the target
trajectory.

Figure 2A illustrates the averaged NV and V movement
trajectories of a representative Parkinson’s disease patient.
The averaged V movement amplitude, at the measurement
time, was 83\% of the corresponding NV amplitude. The
EMG patterns were broadly similar to those observed in
control subjects. Extensor activity commenced prior to overt
movement and grew progressively throughout the extension
trajectories. Flexor EMG was <5\% of maximum and indi-
cated that the patient did not produce appreciable co-contrac-
tion. Small early peaks of flexor activity, presumably of
short-latency reflex origin, are evident shortly after the onset
of vibration. However, as in control subjects, such vibration
reflexes in Parkinson’s disease patients were regularly modest
compared with changes in extensor activity and seem unlikely
to have exerted a marked influence upon movement tra-
jectories.

Figure 2B shows the mean amplitudes of wrist-extension
movements made by the Parkinson’s disease group in the
absence and presence of flexor carpi radialis vibration. In
cases of asymmetrical parkinsonism data refer to the wrist
of the more affected side. Antagonist vibration produced a
significant reduction in the amplitude of extension movements
of Parkinson’s disease patients \( (P < 0.002, \text{ paired } t \text{-test}) \).

**Comparison of vibration-induced alterations in movement trajectories in Parkinson’s disease and healthy subjects**

Although the effects of antagonist vibration upon wrist-
extension movement trajectories in Parkinson’s disease
qualitatively resembled those observed in control subjects,
pronounced quantitative differences were found. Parkinsonian
patients showed a far smaller extent of vibration-induced
undershooting than did healthy individuals.

Figure 3 shows the mean (±SD) ratios of V:NV movement
amplitudes of the patient and control groups. The V:NV
movement ratios of the Parkinson’s disease and control groups
were 0.88 and 0.66, respectively, and were significantly larger
for the Parkinson’s disease group \( (P < 0.001, \text{ Mann–Whitney } U \text{-test}) \). The amplitudes of NV movements did not differ
significantly between the Parkinson’s disease and control
groups \( (P > 0.8, \text{ unpaired } t \text{-test}) \). Thus, the proportionately
smaller influence of vibration in the parkinsonian group did
not arise because of any underlying difference in the sizes
of NV movements in the two groups. Additionally, when
the amplitudes of movements performed during antagonist
vibration were directly compared between the Parkinson’s
disease and control groups it was found that those of the
parkinsonian patients significantly exceeded those of the
healthy subjects \( (P = 0.034, \text{ t-test}) \).

**Vibration-induced alterations of movement trajectories in asymmetrical parkinsonism**

In a subgroup of 14 Parkinson’s disease patients with clearly
asymmetrical signs a comparison was made of the effects
of antagonist vibration on extension movement performance
on the two sides. Clinical scores for bradykinesia, rigidity and
tremor on the two sides are shown for these patients in Table
2. The group average scores for the sum of bradykinesia,
rigidity and tremor (each on a 0–3 ascending scale of severity;
Webster, 1968) were 4.00 and 0.57 for the more and less
affected sides, respectively. This summed score was signi-
cantly greater on the more affected side \( (P < 0.01, \text{ Wilcoxon}) \).

Figure 4A presents records of averaged wrist-extension
movements, in the absence and presence of flexor tendon
vibration, made by the less and more affected wrist of a patient
with asymmetrical parkinsonism. A far more pronounced
vibration-induced undershooting of extension trajectories is
evident on the less affected side (27\%) than on the more
affected side (12\%).

Figure 4B shows the mean amplitudes of NV and V
movements of the more and less affected wrists for the
subgroup of patients with asymmetrical parkinsonism. The
amplitudes of NV movements did not differ significantly
between the two sides \( (P = 0.78, \text{ paired } t \text{-test}) \). On the less
affected side vibration produced a significant reduction in
movement amplitude \( (P < 0.001, \text{ paired } t \text{-test}) \). By contrast,
the amplitudes of V and NV wrist movements did not differ
significantly on the more affected side. In Fig. 4C the
the corresponding V:NV ratios are presented. Pair-wise analysis
Table 2 Clinical details of the 14 Parkinson’s disease patients with asymmetrical signs who were investigated

<table>
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<tr>
<th>Patient</th>
<th>More affected side</th>
<th>Less affected side</th>
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<tbody>
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<td>Average</td>
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</table>

Clinical details of the 14 patients with asymmetrical parkinsonism in whom the effects of vibration upon movement performance were compared on the more and less affected sides. Clinical gradings are based on the Webster (1968) scale, with 0 = no involvement and 3 = severe involvement.

indicated that V:NV ratios were significantly greater on the more affected side (P < 0.05, Wilcoxon).

Studies in Parkinson’s disease patients ‘OFF’ and ‘ON’ medication

Ten Parkinson’s disease patients were investigated ‘OFF’ and ‘ON’ their routine anti-parkinsonian medication. Nine of these patients’ signs were symmetrical when ‘ON’ medication and demonstrated only minor asymmetry when ‘OFF’ medication. The group average for the sum of bradykinesia, rigidity and tremor clinical scores (each on a 0–3 ascending scale of severity; Webster, 1968) were 3.75 and 1.10 for the OFF and ON states, respectively. This summed score was significantly greater in the OFF condition (P < 0.01, Wilcoxon) (see Table 3).

Considering this subgroup of 10 patients as a whole, antagonist vibration produced a significant reduction in movement amplitude in both the unmedicated state (mean values of NV and V amplitudes: 22.5° and 18.9°; P < 0.05, paired t test) and the medicated state (mean values of NV and V amplitudes: 21.5° and 16.5°; P < 0.005). The amplitudes of NV movements did not differ significantly between ‘OFF’ and ‘ON’ states (P > 0.7, paired t test). The mean V:NV ratios of movements made ‘OFF’ and ‘ON’ medication were 0.84 ± 0.15 (SD) and 0.77 ± 0.16, respectively, suggesting a tendency for vibration to produce less undershooting in the unmedicated condition; however, this difference was not statistically significant (P > 0.05, Wilcoxon).

Relationship between vibration-induced alterations of movement trajectories and clinical features in Parkinson’s disease

In the patient group (n = 29) as a whole, no significant correlation was found between the magnitude of vibration-induced undershooting, assessed as V:NV amplitude ratios, observed in individual patients and overall clinical score (Webster rating, 1968) or any of the major clinical signs of bradykinesia, rigidity or tremor of the tested limb (all P > 0.2, Spearman rank correlation coefficient).

Vibration-evoked reflexes in wrist muscles

Vibration-induced undershooting of target extension trajectories, in both healthy subjects and Parkinson’s disease patients, was associated with sustained reductions in extensor EMG; flexor activity was generally low both in the absence and presence of vibration (see Figs 1 and 2). Changes in EMG, most pertinently in the extensors, could potentially arise from alterations in voluntary drive occurring in reaction to the mechanical stimulus and/or vibration-induced reflex effects. In order to assess the likely contribution of the latter type of mechanism, averaged extensor (and flexor) EMGs were obtained during flexor vibration whilst subjects were instructed to attempt to exert a steady level (~15% individual maximum) of voluntary extensor effort under isometric conditions. Analysis concentrated on healthy subjects, since vibration-induced undershooting had been shown to be more pronounced in this group.

All control subjects produced the target levels of isometric
Fig. 4 Effects of antagonist vibration upon the averaged wrist-extension movements made by the wrists of the less and more affected upper limbs of patients with asymmetrical parkinsonism. (A) The averaged \((n = 12)\) V and NV wrist movements made on the two sides. (B) The mean (+SD) amplitudes of V and NV wrist-extension movements on the two sides, made by the group of asymmetrical parkinsonian patients. **"Significant difference between V and NV amplitudes at the \(P < 0.001\) level (paired \(t\) test). (C) The mean ratios (+SD) of the amplitudes of vibrated : non-vibrated wrist-extension movements of the more and less affected limbs. *Significant difference at the \(P < 0.05\) level (Wilcoxon).

Table 3 Clinical details for the 10 parkinsonian patients studied in both unmedicated (OFF) and medicated (ON) states

<table>
<thead>
<tr>
<th>Patient</th>
<th>OFF</th>
<th>ON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bradykinesia</td>
<td>Rigidity</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
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<tr>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>26</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>29</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>1.5</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Clinical gradings are based on the Webster (1968) scale, with 0 = no involvement and 3 = severe involvement.

Extensor force by extensor muscle activation with little or no flexor co-contraction. Examples of the vibration-evoked EMG responses of a control subject are shown in Fig. 5. The overall patterns of activity are illustrated in Fig. 5A, whilst faster sweep speed segments of the records, corresponding to the onset and termination of vibration, are featured in
Vibration-induced movement errors in Parkinson’s disease

Fig. 5 Averaged rectified EMG responses (25 trials) of wrist extensor and flexor muscles to the application of 2-s periods of vibration (105 Hz, 0.7-mm peak-to-peak amplitude) in a control subject (A, B and C) and Parkinson’s disease patient (D, E and F). Subjects exerted a voluntary isometric wrist extensor force, 15% of maximum, immediately prior to the beginning of each trial (with visual feedback of force production) and were requested to maintain a steady level of voluntary effort throughout the trial (in absence of feedback). EMG activity at the commencement (control B, patient E) and termination (control C, patient F) of vibration is shown at a faster sweep speed. In B and E, asterisks indicate early troughs in extensor activity which are believed to represent phasic reflex reciprocal inhibitory responses.

Fig. 5B and C, respectively. Following the onset of prolonged (2-s) periods of flexor vibration, the averaged, rectified, extensor EMGs of control subjects invariably featured one or two early (<100 ms), transient troughs of reduced activity. These were often succeeded by one or two less prominent fluctuations. The initial complex of extensor EMG waves typically died away within 250 ms of the start of vibration and thereafter no further definite waves were evident. In particular, unequivocal examples of increases in activity occurring at the termination of vibration, indicative of a pronounced and synchronized reflex reciprocal disinhibition, were never observed and any indications of such responses were very rare. The flexor EMGs of control subjects commonly featured short-latency (~25 ms), transient, excitatory peaks superimposed on an otherwise low level of activity. Even for subjects whose short-latency reflex pathways were highly excitable, as for the one shown in Fig. 5, tonic activation of the flexor muscle was weak. The EMG records of the three Parkinson’s disease patients studied were generally similar to those of controls. There was, however, a tendency for a greater degree of co-contraction, although flexor activities still remained very modest; in addition, small, sustained excitatory reflexes in the flexor were more evident throughout vibration. The responses of a Parkinson’s disease patient are shown in Fig. 5D–F.

In order to quantify any reductions in extensor activity associated with prolonged flexor vibration, measurements of the levels of activity occurring at 1.65 s after vibration onset were compared with those immediately preceding the commencement of vibration. The former measurement time was chosen to correspond to that for movement trajectories in the main series of experiments. Measurements were made from the averaged, rectified EMG records of individual subjects (see Methods). For the seven control subjects, the mean extensor EMG level at 1.65 s was 12% less than the background (pre-stimulus) level. Statistical analysis indicated that the vibration-induced reduction in extensor activity was significant ($P = 0.02$, paired $t$ test). The group mean of
Additionally, it has been long recognized that the strengths extension trajectories (average et al., 1972) of Parkinson’s disease patients suggested that following similar periods (1.65 s) of flexor vibration, reductions in extensor activity were also elicited. Indeed, the EMG levels of the three patients tended to be more depressed than those of controls (on average by ~30% compared with pre-vibration values).

**Discussion**

The main new finding of the present study was that antagonist (flexor) muscle vibration elicits an abnormally reduced degree of undershooting of slow voluntary wrist-extension movements in Parkinson’s disease. Nevertheless, considering the Parkinson’s disease group as a whole, the patterns of vibration-induced trajectory errors, and altered EMG activity, were qualitatively similar to those found in healthy individuals. This suggests that a quantitative impairment of proprioceptive guidance of voluntary movement exists in Parkinson’s disease which results from a disturbance of normal mechanisms rather than arising as a de novo pathological phenomenon.

**Origin of vibration-induced movement errors in healthy subjects**

Numerous earlier studies in healthy subjects have established that vibration can generate kinaesthetic illusions (Goodwin et al., 1972a, b; Gilhodes et al., 1986) and modify the trajectories of learned voluntary movements (Capaday and Cooke, 1981, 1983; Appenteng and Prochazka, 1983; Lackner, 1984; Sittig et al., 1985; Bullen and Brunt, 1986; Cody et al., 1990). The most commonly observed form of trajectory alteration, as also found in the current experiments, has been a reduction in movement amplitude (and speed), and consequent undershooting of the target, during antagonist vibration. Two broad categories of explanation may be proposed. First, vibration produces appreciable reflex excitation of the antagonist (vibrated) muscle and/or inhibition of the prime mover. Secondly, the CNS (mis)interprets the powerful artificial vibration-induced proprioceptive barrage as representing an erroneously excessive muscle length/movement velocity and initiates a ‘voluntary’ corrective decrease in movement speed. These two types of explanatory mechanism are not, of course, mutually exclusive. Additionally, it has been long recognized that the strengths of vibration illusions and any accompanying reflex effects are commonly independent (Goodwin, et al., 1972a).

It is impossible to disentangle potential, simultaneously occurring voluntary and reflex contributions to our observed vibration-induced undershooting of learned movement trajectories unequivocally. Therefore, to estimate the extent of reflex effects, a series of control experiments, using similar trains of vibration, was undertaken under simpler isometric conditions in which the likelihood of alterations in volitional drive was minimized. Indeed, the finding that when subjects were requested to maintain a steady (15% maximum) extensor effort during vibration their EMG levels (both extensor and flexor) had returned to pre-stimulus values within <0.5 s of the termination of vibration, despite interim fluctuations, is consistent with uniform levels of voluntary activation.

During the isometric experiments background flexor activity was invariably low, as it was in the extension movement task. Although transient short-latency (~25 ms) excitatory reflexes were regularly observed in the flexors, occasionally accompanied by more prolonged phases of slightly increased EMG, the net amount of excitation associated with these responses was inevitably small. By contrast, background extensor EMG was appreciable. The onset of antagonist vibration typically elicited one or two early components of reduced activity, the first commencing at ~40 ms, which were presumably phases of reflex reciprocal inhibition (see Cody and Plant, 1988, 1989). These early waves died away within 250 ms and an apparent plateau was attained. However, quantitative measurements at 1.65 s after the onset of vibration and at a time equivalent to that used in the movement experiments, revealed that extensor EMG was significantly depressed following prolonged stimulation. The level of extensor activity after 1.65 s of vibration was, on average, 12% below pre-stimulus values. Although most probably of reflex origin, this decline in extensor activity cannot be attributed solely to continued operation of short-latency reciprocal inhibitory mechanisms such as those noted at the onset of vibration. If so, termination of vibration would be expected to produce a distinct disinhibitory augmentation of activity at comparable latency; such increases in EMG were not found. Instead, the depression of extensor EMG may plausibly result from the combined action of several relatively weak, long-latency reflex inhibitory pathways.

These findings furnish good evidence that prolonged vibration produces definite reciprocal inhibitory effects, over a long time-scale; these are likely to contribute to the observed undershooting of target trajectories in the main series of experiments. However, the relatively modest size of the tonic reflex inhibitory actions seems incompatible with such mechanisms providing the primary explanation. Although direct quantitative extrapolation between the two types of experiments (movement versus isometric) is untenable, the pronounced degree of vibration-induced undershooting of extension trajectories (average >30%) is far greater than can
be readily accounted for by the reflex reductions in EMG of ~10%, such as those noted in the isometric task.

By elimination, therefore, we believe that the marked vibration-induced undershooting of wrist-extension trajectories shown by our healthy subjects, and the associated reduction in the rate of build-up of extensor EMG occurring largely after the wrist muscles’ reaction (~90 ms; Lee and Tatton, 1978), originated principally from voluntary corrections to perceived deviations from the desired trajectory.

### Abnormal influence of vibration upon movement in Parkinson’s disease

There are several possible explanations of the abnormally reduced vibration-induced undershooting of trajectories which was characteristic of parkinsonian performance. One possibility is that vibration is a less effective stimulant of proprioceptors in Parkinson’s disease. In this context, the dominant category of sensory receptors involved in vibration illusions and movement effects is generally accepted to be muscle spindles and, in particular, spindle primary endings (for discussion see Goodwin et al., 1972a; Cody et al., 1990). There are several arguments against reduced spindle (or other proprioceptor) activation in the Parkinson’s disease group. It seems improbable that ineffective transmission of vibration to muscle receptors occurred in our parkinsonian patients; the method of application of stimulation was highly standardized, palpation confirmed stimulus spread into vibrated muscles and small vibration reflexes were evident which were similar to those elicited in controls. In addition, available evidence from human microneurographic recordings in parkinsonian patients indicates that vibration elicits an essentially normal pattern of muscle spindle discharge (Burke et al., 1977; Mano et al., 1979). Thus, there is no evidence that Parkinson’s disease patients have decreased spindle sensitivity. Alternatively, it might be suggested that a disturbance of vibration reflexes in Parkinson’s disease played a crucial part. At first sight, such a mechanism is attractive since it is well known that some long-latency proprioceptive reflexes are abnormal in Parkinson’s disease and are believed to underlie parkinsonian rigidity (Meara and Cody, 1992). However, a variety of factors contradict this explanation. As was argued above, vibration reflexes appear to make only a minor contribution to the far more pronounced vibration-induced undershooting of healthy individuals. In addition, such an explanation would require either a diminished vibration-induced reflex activation of the antagonist (vibrated) muscle and a resulting decreased braking of the movement and/or a depressed reciprocal reflex inhibition of the prime mover in the parkinsonian patients. No evidence for either of these mechanisms was found in the vibration reflexes recorded electromyographically from a small group of Parkinson’s disease patients under isometric conditions. As for controls, weak excitatory reflexes were observed in the flexor muscles of the patients. If anything, the tonic reflexes appeared to be slightly larger than in controls which probably reflected marginally increased background activities due to a greater tendency to co-contraction. Thus, these findings argue against a diminution of autogenetic (flexor) excitatory reflex action in Parkinson’s disease, with a consequently weaker braking of extension trajectories, as the cause of reduced vibration-induced undershooting. In keeping with the present observations, previous studies have indicated either that phasic (Cody et al., 1986) and tonic (Burke et al., 1972) excitatory vibration reflexes are normal in Parkinson’s disease or that tonic reflexes may be exaggerated, especially in more rigid patients (McLellan, 1975).

Equally, an explanation in terms of a reduction in vibration-induced reciprocal inhibition in Parkinson’s disease is improbable. The evidence from the few previous investigations of reciprocal inhibition between forearm muscles in Parkinson’s disease patients, in which the depression of H-reflexes or on-going EMG produced by antagonist nerve stimulation has been studied, is contradictory. Lelli et al. (1991) reported that the three phases of H-reflex depression, believed due to disynaptic, presynaptic and polysynaptic mechanisms, respectively, were all reduced in parkinsonian patients. By contrast, Nakashima et al. (1994), in a recent reappraisal of the issue, concluded that the first two of these phases of reciprocal inhibition were normal in Parkinson’s disease; furthermore, their observation that the reduction in the voluntary EMG activity elicited by antagonist nerve stimulation was prolonged in Parkinson’s disease patients suggested that certain reciprocal inhibitory mechanisms may be exaggerated in the disease. In the present experiments, protracted flexor vibration, under isometric conditions, produced definite early and tonic reciprocal reductions in the extensor EMG of patients. As for controls, the reflex decline in the patients’ extensor EMG occurring during sustained vibration was fairly modest. However, measurements provided no evidence of a further diminution of tonic reflex reciprocal inhibitory action in Parkinson’s disease which could plausibly account for less undershooting of trajectories.

The absence of any definite disturbances of inhibitory (or excitatory) tonic vibration reflexes amongst the small group of patients in whom they were presently investigated argues against, although does not totally exclude, a reflex contribution to the reduced vibration-induced alterations in movement profiles in the broader patient group. On balance, therefore, we favour an explanation in terms of a derangement of higher-level processing of proprioceptive input in Parkinson’s disease which is largely independent of reflex mechanisms.

The generation of relatively slow (i.e. non-ballistic) voluntary movements is widely presumed to depend upon the CNS comparing motor signals, in the form of corollary discharges from motor centres, with sensory proprioceptive signals of the evolving trajectory (see Goodwin et al., 1972a; Matthews, 1982). On the basis of the comparator model, several possible explanations of our observations of reduced effects of vibra-
tion upon movement trajectories in Parkinson's disease may be advanced. Most simply, vibration evoked either a smaller increamental increase in peripheral proprioceptive discharge in parkinsonian patients or a normally enhanced sensory signal was given a relatively low weighting (versus corollary discharge signals) in the central integrative unit. Arguments against the former possibility have been presented above. Thus, an abnormality of central processing may be suspected. A comparator defect in Parkinson's disease comprising a low sensory feedback gain is a straightforward possibility, although an alternative explanation involving saturation of feedback signals is also plausible. Deranged central processing could produce either a low amplification of sensory input or a pronounced non-linearity of the feedback signal to the comparator in which a ceiling effect existed. In both situations, the output error signal of the comparator, and the associated movement trajectory, would remain relatively unchanged despite substantial increases in peripheral input (e.g. by vibration). In general keeping with this suggestion, several studies have demonstrated that in primates rendered parkinsonian by MPTP treatment, the responses of basal ganglia neurons to somatosensory inputs show distinct abnormalities. For example, pallidal cells exhibit altered resting discharge, a lack of selectivity and exaggerated responsiveness to peripheral inputs (Tremblay et al., 1989; Filion and Tremblay, 1991). Therefore, we propose that saturation of sensory feedback mechanisms within the diseased basal ganglia may underlie abnormalities of proprioceptive guidance in Parkinson's disease.

Implications for movement control in Parkinson's disease

Irrespective of the precise mechanism responsible for the reduced influence of vibration upon intended movements in Parkinson's disease, our observations are consistent with an impairment of proprioceptive regulation which could, in principle, contribute to patients' motor deficits. Moore (1987) has proposed that a disturbance of comparator action occurs in Parkinson's disease and is responsible for patients' characteristic bradykinesia. He found that parkinsonian patients with asymmetrical bradykinesia overestimated the trajectory of the more affected limb when required to match actively-generated bilateral elbow movements. Two possible origins of the overestimation errors were advanced; an increase in the proprioceptive feedback signal to the comparator (i.e. indicating an excessively rapid movement) or a reduction in the corollary discharge signal (i.e. indicating that the required movement was of an inappropriately low speed). Subsequently, Moore (1989) reported that vibration-induced illusions of elbow movement were essentially normal in Parkinson's disease. He interpreted this finding as providing indirect support for the idea that parkinsonian bradykinesia is due to an abnormally weak level of corollary discharge accompanying a given strength of motor command. This might occur, for example, as part of a long-term compensatory mechanism involving tonically enhanced central drive to the spinal circuitry.

Although we also interpret our results as indicating a comparator disturbance in Parkinson's disease, the relationship between the neural mechanisms which were investigated in the present experiments and those whose derangement is responsible for bradykinesia is unclear. Additionally, several of our observations seem inconsistent with Moore's (1987) explanation of bradykinesia. In our experiments, slow practiced movements were deliberately chosen for study in order to minimize any overt effects of patients' inherent bradykinesia; this was essential to allow patients to generate non-vibrated movements of a similar amplitude to those of controls so that valid statistical comparisons of the effects of proprioceptive stimulation could be made. Evidently, the combination of a relatively undemanding task, motor learning and possible compensatory strategies was enough to conceal or override the disturbances of motor control which produce parkinsonian bradykinesia.

At first sight, our results differ in one crucial respect from those predicted by Moore's (1987) account of parkinsonian bradykinesia. Whereas an increase in central comparator responsiveness to peripheral proprioceptive feedback is a feature of Moore's model, the present finding of smaller vibration-induced movement errors in Parkinson's disease suggests a reduction central responsiveness. An explanation which would go some way to reconciling the present findings with those predicted by Moore's (1987) model is that there is an abnormally restricted central modulation of proprioceptive feedback signals in Parkinson's disease. If, as suggested above, a ceiling effect operates due to saturation of proprioceptive mechanisms in the diseased basal ganglia, the actions of especially powerful peripheral afferent inputs, e.g. evoked by vibration, might be preferentially suppressed, whereas the actions of weaker inputs could be relatively normal or even enhanced.

A secondary issue concerns whether or not normal vibration illusions are preserved in Parkinson's disease. Although central processing of proprioceptive input for perceptual and motor control purposes could theoretically involve largely independent mechanisms, a reduction in vibration-induced undershooting of wrist movements in Parkinson's disease, as we observed, might be expected to be associated with a parallel curtailment of movement illusion. By contrast, Moore (1989) reported that a small sample of parkinsonian patients failed to show any definite disturbance of kinaesthetic illusions. However, evidence has recently been provided that static position sense, assessed during active maintenance of joint angle, is impaired in Parkinson's disease (Zia et al., 1996) suggesting that the parkinsonian CNS may be less able to distinguish differences in natural patterns of muscle afferent input. Thus, the issue of kinaesthetic illusions in Parkinson's disease could usefully be re-examined.

Although the relevance, to parkinsonian bradykinesia, of the mechanisms responsible for reduced vibration-induced
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Moore AP. Vibration-induced illusions of movement are normal in Parkinson’s disease: implications for the mechanism of the movement disorder. In: Crossman AR, Sambrook MA, editors. Neural

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References


Moore AP. Vibration-induced illusions of movement are normal in Parkinson’s disease: implications for the mechanism of the movement disorder. In: Crossman AR, Sambrook MA, editors. Neural


Zia S, Cody FWJ, O’Boyle DJ. Impaired human joint position sense in Parkinson’s disease during active maintenance of joint angle [abstract]. J Physiol (Lond) 1996; 494P: 68P.

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