PERFORMANCE OF SIMULTANEOUS MOVEMENTS IN PATIENTS WITH PARKINSON'S DISEASE

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SUMMARY

Ten right-handed patients with Parkinson's disease and 9 normal subjects performed five different types of movements as rapidly as possible in their own time: (1) isotonic elbow flexion through an angle of 15 deg ('flex'); (2) isometric squeezing of a force transducer between thumb and fingers ('squeeze'); (3) isotonic finger flexion ('cut'); (4) simultaneous performance of both 'flex' and 'squeeze'; (5) simultaneous performance of 'flex' and 'cut'. The patients performed the separate movements of 'flex', 'squeeze' and 'cut' more slowly than normals. However, a more striking deficit was seen when a 'flex' and a 'squeeze' had to be performed at the same time, and with the same arm. There was an additional increase in movement times over and above that seen in the separate movements alone. If the patients used both arms ('flex' with the right, 'squeeze' with the left), rather than one, or when a 'flex' and a 'cut' had to be combined in the same arm, only a slight increase in movement times was observed. In normals, however, the speed of individual movements of 'flex', 'squeeze' or 'cut' was the same irrespective of whether they were performed separately or simultaneously.

In any one subject, movement times for the separate components of 'flex' and 'squeeze' varied independently during the performance of the simultaneous movement. Because they remain independent, we suggest that when 'flex' and 'squeeze' are performed at the same time, two separate motor programmes are superimposed to produce the combined movement. In Parkinson's disease there may be a deficit in superimposing two separate motor programmes which leads to the pronounced slowness of simultaneous movements with the same arm.

Comparison of movement times for a 'flex' (but not for a 'squeeze') in the separate and simultaneous movements showed that the degree of clinical akinesia was more closely related to the additional slowness in simultaneous movements than to the slowness seen when the movements were performed separately. The degree of disturbance in superimposing separate motor programmes may determine the amount of clinical akinesia in patients with Parkinson's disease.

INTRODUCTION

One striking clinical feature of akinesia in Parkinson's disease is the difficulty that patients experience when they try to perform two separate motor tasks at the same time. Parkinson's disease is characterized by a combination of tremor, rigidity, bradykinesia, and postural instability, which can severely impair the patient's ability to coordinate movements. The assessment of motor function in Parkinson's disease often involves the evaluation of simple motor tasks, such as limb movements, which can be challenging due to the disease's effects on motor integration and coordination.

In Parkinson's disease, the brain's capacity to coordinate movements is impaired, leading to difficulties in performing simultaneous movements. This is particularly evident in tasks that require the simultaneous execution of two movements. The study by Benecke et al. (1986) aimed to investigate the performance of simultaneous movements in patients with Parkinson's disease and compare it with that of normal subjects.

The researchers selected five different types of movements: isotonic elbow flexion, isometric squeezing of a force transducer, isotonic finger flexion, simultaneous performance of both 'flex' and 'squeeze', and simultaneous performance of 'flex' and 'cut'. These movements were performed by both patients with Parkinson's disease and normal subjects, who were asked to perform the movements as rapidly as possible in their own time.

The results showed that the patients with Parkinson's disease performed the separate movements of 'flex', 'squeeze', and 'cut' more slowly than the normal subjects. However, a more striking deficit was observed when a 'flex' and a 'squeeze' had to be performed at the same time, and with the same arm. This deficit was even more pronounced when the patients used both arms, or when a 'flex' and a 'cut' were combined in the same arm.

In normals, the speed of individual movements of 'flex', 'squeeze', or 'cut' was the same irrespective of whether they were performed separately or simultaneously. However, in any one subject, movement times for the separate components of 'flex' and 'squeeze' varied independently during the performance of the simultaneous movement. This suggests that when 'flex' and 'squeeze' are performed at the same time, two separate motor programmes are superimposed to produce the combined movement. In Parkinson's disease, there may be a deficit in superimposing two separate motor programmes, which leads to the pronounced slowness of simultaneous movements with the same arm.

Comparison of movement times for a 'flex' (but not for a 'squeeze') in the separate and simultaneous movements showed that the degree of clinical akinesia was more closely related to the additional slowness in simultaneous movements than to the slowness seen when the movements were performed separately. This suggests that the degree of disturbance in superimposing separate motor programmes may determine the amount of clinical akinesia in patients with Parkinson's disease.

The study by Benecke et al. (1986) provides valuable insights into the motor impairments observed in Parkinson's disease and highlights the importance of understanding the mechanisms underlying the coordination of movements in this condition. Further research in this area is crucial for developing effective treatments that can improve the patients' ability to perform coordinated movements.
same time. Schwab et al. (1954) drew attention to the vivid description given by one of their patients of his difficulties in daily life. ‘When walking across the hotel lobby in front of the usual number of strangers to pay his bill, he reached into his inside pocket with his left hand to get his wallet. At once he stopped walking, standing immobile before the strangers. Becoming aware of this, he then resumed walking but his left hand remained in his inside pocket, suggesting perhaps a planned holdup’.

The only attempts to analyse this deficit physiologically were made over twenty years ago. Schwab et al. (1954) asked patients to trace the outline of a triangle and to draw perpendicular lines with their dominant hand while squeezing the rubber bulb of a sphygmomanometer repetitively with the other hand. In addition to rapid fatigue in the repetitive task, the most striking effect was that the patients avoided making both actions together. Instead they preferred to perform the tasks sequentially. They would first draw a line, then squeeze the bulb, draw another line, and so on. Talland and Schwab (1964) used a similar task in which patients had to press down a tally counter with the nondominant hand and simultaneously pick up beads with a pair of tweezers with the opposite hand. Performance of these two manual tasks together markedly decreased the rate of counter pressing, but changed the rate of bead picking to a lesser extent. The patients favoured the performance of bead picking and avoided counter pressing.

The results of Schwab and his colleagues reflect the motor problems of patients with Parkinson’s disease, but are difficult to interpret in detail. In both experiments the patients concentrated on the more complex task of drawing or using tweezers at the expense of the apparently simpler repetitive movement. The patients might have chosen this strategy because they thought that the drawing task was the more important of the two; for example, they may have decided that completion of the drawing task signified the end of the test session, rather than having to go on to perform a given number of squeezes. Alternatively, the deficit that they described might have been one of sharing or switching attention between the two motor tasks; patients may have been unable to perform simultaneous movements because they could not divide attention between them. Finally, the deficit could have been purely a motor phenomenon; either patients were unable to perform simultaneous movements, or they could do so but preferred not to because they had experienced that their performance deteriorated so badly under such circumstances that they could improve it only by executing the tasks sequentially.

In order to investigate the deficit in simultaneous movements in more detail, we devised much simpler tasks than those of Schwab et al. (1954). The two movements that we examined were isotonic flexion at the elbow combined with either isometric squeezing of a force transducer between the fingers and thumb, or isotonic flexion of the index finger and thumb. Each movement could be made separately, and the performance was then compared with that seen when both movements were made at the same time. The two movements were so rapid that there was no need to switch attention between them, as in the tasks of Schwab
and colleagues (1954). Part of this work has been published briefly in abstract form (Benecke et al., 1985).

**PATIENTS AND METHODS**

The parkinsonian patient group comprised 10 men with at least one year's history of idiopathic Parkinson's disease. All patients but 1 were treated with L-DOPA and showed a pronounced positive response to this drug. Their clinical features are summarized in Table 1. Seven of the patients were studied 10 to 18 h after the last oral dose of L-DOPA (OFF therapy); 2 other patients were tested in the ON state; however, they still had considerable motor impairment (see Table 1). For an objective evaluation of motor impairment in the right arm, a pegboard and a two-point touching test was undertaken in 8 of the 10 patients. In a modification of the usual pegboard test, the patients had to place all 25 pegs with their right hand as fast as possible. The score was the time taken to complete this task (for further details of the test procedure, see Costa et al., 1963). In the two-point touching test the patients had to touch alternately one of two targets each 10 cm in diameter and 60 cm apart with their right index finger as frequently as possible. The score was the number of touches within 30 s. The results obtained in the patient group were compared with those from a group of 9 normal subjects (see Table 2). The mean age of this normal group (47.0 years) was slightly but not statistically significantly ($P > 0.05$) lower than that of the patients (58.1 years). All subjects were right-handed and gave informed consent for the procedures used.

'Squeeze' and 'Flex' Tasks

Subjects were seated comfortably with their right arm abducted to 90 deg at the shoulder. The semipronated forearm rested on a lightweight manipulandum which was pivoted so as to be coaxial with the elbow joint. The angular position of the elbow was monitored by a sensitive potentiometer attached to the pivot. At the end of the manipulandum, and adjusted according to the length of the forearm, was a U-shaped bar of aluminium which could be grasped between the thumb and fingers. A strain gauge was mounted on one of the vertical arms of the U so that the force of squeeze could be monitored (fig. 1).

<table>
<thead>
<tr>
<th>Case</th>
<th>Age* (yrs)</th>
<th>Sex</th>
<th>Akinesia</th>
<th>Tremor</th>
<th>Rigidity</th>
<th>PBT* (s)</th>
<th>TPTT*</th>
<th>Treatment</th>
<th>Time after last medic.</th>
</tr>
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<td>1 (J.M.)</td>
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<td>M</td>
<td>++++</td>
<td>+</td>
<td>+</td>
<td>110</td>
<td>89</td>
<td>Levodopa</td>
<td>2</td>
</tr>
<tr>
<td>2 (W.R.)</td>
<td>37</td>
<td>M</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>75</td>
<td>90</td>
<td>Levodopa</td>
<td>10</td>
</tr>
<tr>
<td>3 (H.S.)</td>
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<td>M</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>120</td>
<td>79</td>
<td>Levodopa</td>
<td>18</td>
</tr>
<tr>
<td>4 (A.R.)</td>
<td>55</td>
<td>M</td>
<td>+++</td>
<td>0</td>
<td>+</td>
<td>89</td>
<td>84</td>
<td>Levodopa</td>
<td>12</td>
</tr>
<tr>
<td>5 (M.C.)</td>
<td>61</td>
<td>M</td>
<td>(++)*</td>
<td>+</td>
<td>+</td>
<td>95</td>
<td>82</td>
<td>Levodopa</td>
<td>12</td>
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<tr>
<td>6 (R.C.)</td>
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<td>M</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>108</td>
<td>65</td>
<td>Levodopa</td>
<td>16</td>
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<td>7 (A.G.)</td>
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<td>M</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>99</td>
<td>78</td>
<td>Levodopa</td>
<td>10</td>
</tr>
<tr>
<td>8 (A.B.)</td>
<td>52</td>
<td>M</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>107</td>
<td>88</td>
<td>Levodopa</td>
<td>14</td>
</tr>
<tr>
<td>9 (A.S.)</td>
<td>54</td>
<td>M</td>
<td>+(+)</td>
<td>+</td>
<td>+</td>
<td>107</td>
<td>88</td>
<td>Levodopa</td>
<td>14</td>
</tr>
</tbody>
</table>

* The motor functions of the patients (akinesia, tremor, rigidity) were assessed independently by two of the authors using conventional clinical examination of the whole body. A scaling from 0--+++ was used for each symptom. In 2 patients (Cases 5 and 9) there was slight disagreement over the amount of akinesia. In these patients a (+) score was introduced. $^a$ PBT = score of pegboard test as the time taken to place 25 pegs. $^b$ TPTT = score of two-point touching test as number of touches within 30 s. $^c$ Mean age 58.1 ± 10.4 yrs. n.a. = not available.
Subjects were asked to perform three different tasks: (1) flex the elbow joint as rapidly as possible in their own time through an angle of 15 deg from a starting angle of 135 deg (‘flex’ task); (2) squeeze the strain gauge as rapidly as possible in their own time up to a force of 30 N (‘squeeze’ task); (3) execute both tasks simultaneously as rapidly as possible in their own time (‘both together’ task). The three tasks were performed in a cyclic order. Both elbow position and amount of grip force were displayed as two vertical bars 2 cm in length on an oscilloscope screen 60 cm before the subjects. Each individual performed about 5 practice trials of each of the 3 tasks; thereafter 10 single trials of each type were collected.

**TABLE 2. MOVEMENT PERFORMANCE IN THE UNILATERAL ‘SQUEEZE’ AND ‘FLEX’ (NORMAL SUBJECTS)**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>MTflex (ms)</th>
<th>Tsqu (ms)</th>
<th>Increase&lt;sup&gt;a&lt;/sup&gt; MTflex</th>
<th>Increase&lt;sup&gt;a&lt;/sup&gt; Tsqu</th>
<th>Bi-Opp&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Separately</th>
<th>Simultaneously</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (R.B.)</td>
<td>35</td>
<td>M</td>
<td>175 (8)*</td>
<td>138 (9)</td>
<td>-5</td>
<td>-7</td>
<td>28 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (M.G.)</td>
<td>36</td>
<td>M</td>
<td>190 (9)</td>
<td>167 (15)</td>
<td>-20</td>
<td>-21</td>
<td>34 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (M.R.)</td>
<td>66</td>
<td>M</td>
<td>264 (30)</td>
<td>168 (27)</td>
<td>-16</td>
<td>24</td>
<td>31 (7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (J.D.)</td>
<td>31</td>
<td>M</td>
<td>198 (21)</td>
<td>170 (12)</td>
<td>-23</td>
<td>27</td>
<td>26 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 (J.R.)</td>
<td>30</td>
<td>M</td>
<td>223 (26)</td>
<td>118 (11)</td>
<td>-13</td>
<td>4</td>
<td>24 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (B.D.)</td>
<td>33</td>
<td>M</td>
<td>226 (26)</td>
<td>130 (16)</td>
<td>0</td>
<td>5</td>
<td>28 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 (J.S.)</td>
<td>63</td>
<td>M</td>
<td>309 (27)</td>
<td>190 (15)</td>
<td>-35</td>
<td>8</td>
<td>33 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 (F.R.)</td>
<td>62</td>
<td>F</td>
<td>244 (27)</td>
<td>158 (12)</td>
<td>-7</td>
<td>7</td>
<td>29 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 (F.D.)</td>
<td>67</td>
<td>M</td>
<td>237 (44)</td>
<td>168 (28)</td>
<td>-13 (12)</td>
<td>0 (15)</td>
<td>29 (3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Separately = measurements of movement time for elbow flexion (MTflex) and isometric squeeze (Tsqu) when executed separately.  
Simultaneously = measurements of MTflex and Tsqu in the simultaneous performance of both movements.  
Increase of the mean MTflex and Tsqu in the ‘both together’ task when compared with MTflex and Tsqu when executed separately.  
Bi-Opp = interonset latency between recruitment of biceps and opponents in the ‘both together’ task.  
Mean value (± SD) of 10 consecutive trials.  
† Mean (SD) = mean values ± SD (n = 9) of the mean values obtained in each subject.

Two sets of experiments were performed. In one, both ‘flex’ and ‘squeeze’ were made using the right arm (unilateral task). In the other, elbow flexion was made with the right arm and ‘squeeze’ with the left arm (bilateral task). To achieve this, the force transducer was removed from the manipulandum and placed at the end of the left arm rest, where it could be grasped with the left hand. A weight equivalent to that of the force transducer was added to the end of the manipulandum on the right side in order to maintain a constant inertia.

‘Cut’ and ‘Flex’ Task

For measurements of an isotonic finger flexion (‘cut’), a vertical rod was attached to the manipulandum so that it was positioned between the thumb and the index finger of the pronated arm. The thumb and the middle finger were placed in the arms of a pair of scissors. The intersection of the scissors arms was connected to a potentiometer so that finger flexion movements acting on the scissors could be measured. Subjects were asked to perform a ‘cut’ movement from a starting angle of 135 deg (between the scissors arms) to an angle of 45 deg.

**Recordings and Data Analysis**

Electromyographic activity was recorded with surface electrodes over elbow flexors (biceps brachii, brachioradialis (BRR)) and extensors (triceps), wrist muscles (flexor carpi radialis (FCR), extensor carpi radialis (ECR)), and finger muscles (opponens pollicis (opponens), flexor pollicis longus (FPL), first dorsal intersosseous (interosseous), extensor digitorum communis (EDCo)). Elbow and
Fig. 1. Paradigm for testing the execution of simultaneous movements. Subjects were asked to perform a 15 deg elbow flexion ('flex') and an isometric opposition of thumb to fingers to exert a force of 30 N ('squeeze') separately or simultaneously. All movements had to be performed self-paced and with maximal speed. Duration of the elbow movement time (MTfl) was measured by visual inspection of the velocity signal. Force rise time (Tsqu) was measured from onset to peak of the force signal. Starting and target positions as well as the position and force responses were displayed on an oscilloscope screen 60 cm before the subjects.

finger positions, velocities (electronically derived from the position signals), force and rectified EMG signals were recorded by a PDP 12 computer with a sampling rate of 500 Hz per channel. The EMG signals were preamplified (Devices 3160 preamplifier with high and low pass filters set at 80 Hz and 2.5 kHz (3 dB points) respectively), then amplified (Devices 3120 amplifier) and processed (Devices signal processor type 4010).

Measurements were made on each single record using the computer display unit. Duration of the elbow ('flex') and finger movement ('cut') times (MTfl, MTcut) and onset of muscle recruitment were measured by visual inspection of the velocity signal (onset to zero crossing) and the EMG signals. Force rise time ('squeeze') (Tsqu) was measured from onset to peak of the force signal. Student's t test (paired or unpaired, as appropriate) was used to analyse the data. Linear correlation coefficients were used to assess the relationship between scores of pegboard and two-point touching tests, and measurements of movement times. Spearman's test of rank correlation was used to test the relation between clinical akinesia scores and movement times.

RESULTS

Simultaneous Unilateral 'Squeeze' and 'Flex' Task

Normals. Fig. 2 shows the averaged performance of 10 trials in a single representative normal individual in the 'flex', 'squeeze' and 'both together' tasks. Each movement was performed rapidly with a single peak velocity. In all subjects, the
movement times for the 'flex' and the 'squeeze' task were the same irrespective of whether they were performed separately or simultaneously (Table 2). In addition, we examined whether there was any relation between the movement times for 'flex' and 'squeeze' when subjects performed the 'both together' tasks. Whereas the movement times varied from trial to trial in each individual, there was no correlation between times for 'flex' and 'squeeze' in the simultaneous task. The mean linear correlation coefficient from 10 trials in each normal subject was 0.16 ± 0.30 (range from -0.4 to +0.6; \( P > 0.05 \)).

The EMG pattern in the 'flex' task consisted of the usual three burst ballistic pattern in biceps and triceps. This was accompanied by activity in many other muscles of the arm. The synergists, brachioradialis and flexor carpi radialis, were recruited about 10 ms after biceps. In those subjects in whom it was recorded, extensor carpi radialis appeared to function as an antagonist like the triceps. Activity was also present in flexor pollicis longus, first dorsal interosseous and opponens pollicis. Onset of EMG activity in opponens had a mean latency after
biceps of 32 ± 9 (SD) ms. This may have been an automatic adjustment to allow the fingers to remain in contact with the squeeze device.

The ‘squeeze’ task was achieved by synergistic coactivation of finger flexor and thenar muscles. There was an early peak of EMG activity which was at least 100% larger than the subsequent tonic activity needed to sustain the required isometric force (fig. 2b). Flexor and extensor carpi radialis showed cocontraction necessary to stabilize the wrist joint. In 5 subjects there was also some activity in biceps and triceps. This consisted of either a cocontracting or an alternating pattern of EMG bursts. Unlike in the ‘flex’ task, in the ‘squeeze’ task both proximal and distal muscles were activated at the same time.

When the tasks were performed ‘both together’, the EMG pattern resembled that expected from superimposition of the two separate movements. However, proximal and distal muscles were not recruited simultaneously. As in the ‘flex’ task, there again was a delay of 29 ± 3 ms between EMG onset in biceps and opponens. However, it should be emphasized that in contrast to the order of muscle recruitment, the mechanical onset of ‘squeeze’ preceded that of flexion (fig. 2c). This was probably due to the difference in electromechanical delay in the isometric and isotonic tasks. It had the result that when elbow flexion had started, the subject had already grasped the squeeze device so that any loss of contact with it was prevented.

Patients with Parkinson’s disease. Fig. 3A shows the average performance of a single representative patient in the ‘flex’, ‘squeeze’ and ‘both together’ tasks. The data from all 10 patients are summarized in Table 3. The separate movements of ‘flex’ and ‘squeeze’ were slower in the patients than in normal subjects (P < 0.001 for both ‘flex’ and ‘squeeze’). The majority of patients had double or multiple peaks in the velocity trace of the ‘flex’ task, accompanied by multiple bursts of

### Table 3. Movement Performance in the Unilateral ‘Squeeze’ and ‘Flex’ Task (Patients)

<table>
<thead>
<tr>
<th>Case</th>
<th>MTfl (ms)</th>
<th>Tsqu (ms)</th>
<th>MTfl (ms)</th>
<th>Tsqu (ms)</th>
<th>Increase MTfl (ms)</th>
<th>Increase Tsqu (ms)</th>
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<td>1</td>
<td>347 (47)</td>
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<td>638 (116)</td>
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<td>449 (88)</td>
<td>210 (28)</td>
<td>125</td>
<td>16</td>
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</table>

Mean values of MTfl and Tsqu when executed separately were highly significantly prolonged in the patients (P < 0.001) when compared with those of normal subjects (Table 2). **Increase of MTfl and Tsqu in the ‘both together’ task are significant (P < 0.005). For further explanations, see footnote to Table 2.**
FIG. 3. Execution of single and simultaneous movements ('squeeze' and 'flex') in a patient with Parkinson's disease (Case 3). In A, averaged responses of 10 trials are shown. In B, representative single trials are shown. Note different time scales in A and B. Vertical lines in B indicate the onset of activity in the prime mover.

EMG activity in biceps and triceps (see below). In the 'both together' task there was a substantial further increase in movement time. Movement time for elbow flexion increased in the patients by an average of 208 ± 85 ms (P < 0.005); movement time for 'squeeze' increased by 88 ± 50 ms (P < 0.005). Patients who had a large increase in movement times for 'flex' in the 'both together' task also had large increases in movement times for 'squeeze' and vice versa (r = 0.74; P < 0.05). As in normal subjects, movement times for 'flex' and 'squeeze' in the combined task varied from trial to trial in each subject. However, when each individual was
analysed separately, there was no relationship between the movement times for 'flex' and 'squeeze' in the combined task for 9 of the 10 patients (average correlation coefficient for 10 trials in each subject was 0.15 ± 0.40 (SD): range —0.5 to +0.77. Subject 2 with a correlation coefficient of 0.77 had the only significant correlation ($P < 0.05$)).

The question arises as to whether these changes in movement times were related in any way to the degree of clinical akinesia. The following analysis is confined to absolute increases in movement times in the simultaneous task rather than to percentage changes. The reason for this choice is twofold. First, percentage changes are biased by performance in each single movement. We had no a priori reason to believe that movement time in single movements was related to increase in movement times in simultaneous movements. Secondly, clinical estimates of akinesia probably rely more on absolute increases in movement times than on proportional changes.

To answer this question we have correlated movement times with the clinically established degree of akinesia (fig. 4), and with two objective measure of akinesia (pegboard test, and two-point touching test). Time taken for elbow flexion on its own was not correlated with any of these three measures. In contrast, in the 'both together' task the increase in movement time for elbow flexion was strongly correlated with both the clinical rating (see fig. 4) and the score on the pegboard test ($r = 0.81; P < 0.025$). Results for the 'squeeze' task were somewhat different. Time taken to perform a 'squeeze' alone was well correlated with clinical akinesia (fig. 4) and with the score on the pegboard test ($r = 0.84; P < 0.01$). However, the increase in the 'squeeze' time in simultaneous movements was correlated only with the clinical rating scale (fig. 4). Scores in the two-point touching test were not related to any measures of movement time in the present experiments, and were not correlated with clinical ratings (correlation coefficient, $r = -0.49; P > 0.05$), or pegboard scores ($r = -0.4; P > 0.05$). To summarize these correlations, the most striking finding was that movement times in the separate flexion task were not correlated with measures of akinesia whereas increases in movement time in the 'both together' task showed the highest correlation. However, times taken to squeeze alone were correlated with measures of akinesia, but the increase in the 'both together' task were less clearly correlated with akinesia.

The EMG pattern responsible for all three movements was more variable both in any one patient, and also between different patients, than it was in normal individuals. In the 'flex' task some patients had a normal three burst pattern in most trials, others showed multiple repetitive bursts which alternated between biceps and triceps, and others had no discernible bursts in the EMG and showed tonic activity in biceps and triceps. The synergist muscles, brachioradialis and flexor carpi radialis, behaved like biceps in individual trials. There was also activity in the muscles of the hand, which began, as in normal subjects, an average of 30 ms after onset of biceps EMG (fig. 3b and Table 3).

In the 'squeeze' task there was a reduction (less than 100% larger than subsequent
Fig. 4. Relation between the degree of clinically evaluated akinesia and movement times in patients with Parkinson's disease. A shows the values of the increase in movement times for elbow flexion ('flex') (MTfl) and 'squeeze' (Tsqu) when the tasks were performed simultaneously. B shows the absolute values of the movement times when these two tasks were executed separately. Each point represents the mean of 10 movements. Akinesia rating was correlated with values for the increase in movement times (A) for both 'flex' (Spearman's $\rho = 0.97$; $P < 0.001$), and 'squeeze' ($\rho = 0.7$; $P < 0.05$). However, when movement times for separate movements (B) were examined, akinesia correlated only with duration of 'squeeze' ($\rho = 0.83$; $P < 0.01$), but not with duration of 'flex'. Filled circles = MTfl. Open circles = Tsqu.

tonic activity) or absence of the phasic peak in the EMG from the finger muscles (see fig. 3A) compared with normal subjects. Coactivity in proximal muscles occurred synchronously as in normals (fig. 3A, B).

In contrast to normal individuals, the EMG pattern in the 'both together' task was not that expected from superimposition of behaviour in the separate tasks alone. If a patient had a preserved three burst pattern in elbow flexion, this changed to a multiple burst pattern or was replaced by tonic activity of biceps and triceps...
Patients who already exhibited multiple bursts in the 'flex' task changed to an exclusively tonic pattern in the 'both together' task. Changes in synergist activity of brachioradialis and flexor carpi radialis followed that of biceps. Finger muscles showed a further decrease of the peak, or even a slow rise of activity rather than a step-like increase in EMG, during the 'both together' task. Despite these changes, the onset of opponens activity in the combined movement was still 30 ms later than biceps.

The increase in time taken for elbow flexion was only seen when the 'squeeze' task had to be initiated at the same time as the 'flex' task. When one patient (Case 5) was instructed first to 'squeeze' and then, 5 to 10 s later, to 'flex', there was no change in movement time as compared with 'flex' alone.

**Simultaneous Bilateral 'Squeeze' and 'Flex' Task**

**Normals.** When the 'flex' task was performed with the right arm and the 'squeeze' with the left arm, normal subjects again executed both 'flex' and 'squeeze' movements with similar movement times irrespective of whether they were performed separately or simultaneously (see Table 4). Even though all the subjects were right-handed, comparison of Table 2 with Table 4 shows that the movement time for the 'squeeze' on both sides was the same ($P > 0.05$).

**Parkinson's disease.** When patients performed the 'both together' task with their
TABLE 4. MOVEMENT IN THE BILATERAL ‘SQUEEZE’ AND ‘FLEX’ TASK

<table>
<thead>
<tr>
<th>Case</th>
<th>MTfl* (ms)</th>
<th>Tsqu* (ms)</th>
<th>Increase MTfl (ms)</th>
<th>Increase Tsqu (ms)</th>
<th>Bi-Opp (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>361 (27)</td>
<td>188 (15)</td>
<td>385 (49)</td>
<td>218 (34)</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>315 (38)</td>
<td>196 (21)</td>
<td>326 (42)</td>
<td>204 (21)</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>274 (29)</td>
<td>184 (33)</td>
<td>288 (25)</td>
<td>197 (12)</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>405 (49)</td>
<td>180 (13)</td>
<td>453 (106)</td>
<td>212 (24)</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>336 (52)</td>
<td>204 (19)</td>
<td>364 (51)</td>
<td>231 (28)</td>
<td>28</td>
</tr>
</tbody>
</table>

Mean (SD) 338 (49) 190 (10)

Mean (SD)
Controls 224 (47) 164 (21)

Measurements of 5 patients with Parkinson's disease (mean age 64.4 ± 8 (SD) yrs) and 5 age-matched controls (mean age 52.6 ± 12 (SD) yrs).

* 'Flex' task performed with right arm. b 'Squeeze' task performed with left arm. c 'Flex' with right arm and 'squeeze' with left arm performed simultaneously. * Increase of MTfl and Tsqu significant (P < 0.05).

For further explanations, see footnote to Table 2.

FIG. 6. Contrasting effects of movement performances in simultaneous ‘flex’ and ‘squeeze’ undertaken either with the same or opposite arms in a patient with Parkinson's disease (Case 5). A, separate elbow flexion (right arm). b, simultaneous performance of an elbow flexion and an isometric ‘squeeze’ with the same arm (right). c, simultaneous execution of an elbow flexion by the right arm with a ‘squeeze’ by the left arm. d, separate ‘squeeze’ with the right arm. e, separate ‘squeeze’ with the left arm. A–E show single trials. Calibrations in c apply to all trials.
two arms there was only a slight increase in movement times compared with each task executed separately (25 ± 13 ms increase for 'flex' (P < 0.05); 22 ± 10 ms increase for 'squeeze' (P < 0.05)). Concomitantly the EMG patterns also were preserved in the 'both together' task. A comparison of performance in unilateral and bilateral movements is shown for one patient in fig. 6 and the combined data summarized in Table 4. Although the bilateral movements were investigated on a different day to the unilateral movements, the movement times for the individual 'flex' and 'squeeze' tasks were very similar on both occasions. Thus, like normal individuals, the left-handed 'squeeze' was made as rapidly as the right-handed 'squeeze'. The exception to this was Case 7 who made faster movements in the bilateral task than in the unilateral. We ascribe this to fluctuations in his clinical disability between the times of testing.

As in the unilateral 'squeeze' and 'flex' task, there was no correlation in any of the normal subjects or patients between the movement times for 'flex' and 'squeeze' in the combined (bilateral) task.

**Simultaneous Unilateral 'Cut' and 'Flex' Task**

Fig. 7 shows a representative example of movement performance in the separate 'flex', 'cut' and 'both together' tasks in a patient with Parkinson's disease. During the separate 'cut' task (fig. 7B), opponens acted as an agonist for thumb movement,

![Diagram](image-url)

**Fig. 7.** Execution of 'flex' and 'cut' when performed separately and simultaneously (Case 8). Single trials are shown. A, elbow flexion ('flex'); B, finger flexion ('cut'); C, their simultaneous execution. Calibrations for elbow position (top traces), finger position (second from top traces), rectified EMG signals (remaining traces), and time apply to A, B, and C. Abbreviations for muscles as in Methods.
and extensor digitorum communis as antagonist for finger flexion. In addition, synchronous coactivity in biceps and triceps was present. Such coactivation had been observed in the unilateral 'squeeze' and 'flex' task and probably is responsible for stabilizing the elbow joint. The separate isotonic finger flexion ('cut') was slower in patients with Parkinson's disease than in normals \((P < 0.001;\) see Table 5). When patients performed the 'cut' movement at the same time as elbow flexion ('both together') (fig. 7c) there was an additional increase in movement times \((34 \pm 25 \text{ ms increase for 'flex'} (P < 0.01); 22 \pm 17 \text{ ms increase for 'cut'} (P < 0.05); \) see Table 5). However, the degree of slowing was much less than that observed in the other unilateral task ('squeeze' and 'flex'; see Table 3).

As with the other tasks, there was no correlation in any of the normal subjects or patients between the movement times for 'flex' or 'cut' in the combined task.

**DISCUSSION**

Extra Slowness of Simultaneous Movements in Parkinson's Disease

It is well known that patients with Parkinson's disease move more slowly than normal subjects in tasks involving movement at a single joint (Draper and Johns, 1964; Hallett \textit{et al}., 1977). It was the aim of the present study to test whether any additional motor deficit is apparent when patients attempt to make two movements at the same time. The striking result was that in the patients, there was a dramatic increase in movement times when the two movements of 'flex' and 'squeeze' had to be performed together with the same arm, as compared with that seen when each movement was performed separately. A smaller increase in movement times could also be observed when 'flex' and 'squeeze' were performed with different arms or when movements of 'flex' and 'cut' were combined in the same arm. The

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**TABLE 5. MOVEMENT PERFORMANCE IN THE UNILATERAL 'CUT' AND 'FLEX' TASK**

<table>
<thead>
<tr>
<th>Case</th>
<th>( MT_{fl} ) (ms)</th>
<th>( MT_{cut} ) (ms)</th>
<th>( MT_{fl} ) (ms)</th>
<th>( MT_{cut} ) (ms)</th>
<th>Increase ( MT_{fl} ) (ms)</th>
<th>Increase ( MT_{cut} ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>317 (32)</td>
<td>184 (12)</td>
<td>335 (40)</td>
<td>189 (13)</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>282 (28)</td>
<td>194 (14)</td>
<td>298 (27)</td>
<td>207 (18)</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>302 (50)</td>
<td>202 (15)</td>
<td>344 (49)</td>
<td>252 (18)</td>
<td>42</td>
<td>50</td>
</tr>
<tr>
<td>9</td>
<td>304 (44)</td>
<td>217 (19)</td>
<td>352 (48)</td>
<td>239 (18)</td>
<td>48</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>352 (32)</td>
<td>192 (16)</td>
<td>399 (28)</td>
<td>212 (19)</td>
<td>45</td>
<td>20</td>
</tr>
</tbody>
</table>

| Mean (SD) | 311 (26) | 198 (12) | 346 (36) ++ | 220 (25) * | 34 (15) | 22 (17) |

| Mean (SD) | 177 (37) | 160 (8) | 176 (41) | 157 (10) | -1 (1) | -3 (2) |

Measurements of 5 patients with Parkinson's disease (mean age 59.4 ± 10 (SD) yrs) and of 5 age-matched controls (mean age 52.2 ± 18 (SD) yrs).

* Increase of \( MT_{cut} \) significant \((P < 0.05);\) ++ Increase of \( MT_{fl} \) significant \((P < 0.01).\) For further explanations, see footnote to Table 2.
increase could not have been due to differences in switching attention between the two tasks, since in normal subjects they were both complete in less than 250 ms. Such rapid movements are believed to be preprogrammed (or 'ballistic') and relatively immune to control by feedback mechanisms. Neither was there any evidence for cognitive impairment in our simple tasks which might explain the patients' difficulties. They easily understood what was required and performed the tasks as readily as the normal group. We conclude that in patients with Parkinson's disease there is a pure motor deficit in performance of two different movements at the same time.

Each single simple movement, either the 'flex', the 'cut' or the 'squeeze', was performed more slowly than normal, because of failure to deliver a large enough initial agonist EMG burst to the prime mover. The relative timing of activation in agonist, antagonist and synergist muscles was not abnormal in the patients with Parkinson's disease, but the initial agonist EMG activity was inappropriately scaled to produce the normal velocity of muscle contraction. The observation that the muscle recruitment order, for both the simple and simultaneous task, was normal confirms the general view that Parkinson's disease produces greater deficits in the speed of movement than in their spatiotemporal coordination (Marsden, 1984).

Relation between Movement Times and Akinesia ('Squeeze' and 'Flex' Task)

The patients' movements were slower than those of the normal group in both the 'flex' and 'squeeze' task. This confirms the results of previous workers who used isotonic movements at the wrist, elbow and shoulder, but to our knowledge it is the first demonstration that isometric movements may be equally affected by the disease. Although movement time in a simple isotonic movement is slow in Parkinson's disease, the degree of slowing is often not closely related to the degree of clinical akinesia (see Berardelli et al., 1986). This was evident in the 'flex' task studied here. It showed no correlation with any of the measures of akinesia that we employed. However, a much closer correlation with akinesia was found for the degree of extra slowing when 'flex' and 'squeeze' were undertaken simultaneously with the same arm. It may be that an important part of the clinical estimation of akinesia is the evaluation of such simultaneous movements. Certainly a principal component of the pegboard test is a combined squeeze of the peg and flex of the arm to move the peg from hole to hole. The two-point touching task in contrast might have been expected to be closely related to simple movement time of 'flex'. In our experiments, there was no correlation between this measure of akinesia and any of the movement times. This result may have been influenced by an effect of fatigue on the repetitive movements needed to perform the two-point touching task.

The patients' performance in the 'squeeze' task differed in several ways from that in the 'flex' task. First, time taken for simple 'squeeze' was well correlated with measures of akinesia, unlike that of 'flex'. Secondly, in simultaneous movements,
the extra time taken for 'squeeze' was less than the increase for 'flex'. (This was particularly clear in the absolute values, but also was true in terms of percentage increase in movement time: 159% ± 6 (SE) for 'flex' versus 139% ± 6 (SE) for 'squeeze'; P < 0.05.) We have no explanation for these differences between 'flex' and 'squeeze' at the present time. They may be related to the isotonic and isometric natures of the tasks. Since the main purpose of this paper is to focus on the increase in movement times in simultaneous tasks, we shall not discuss this finding further. However, it is of interest that in clinical circumstances, akinesia usually is measured by estimation of performance in isotonic tasks (e.g., speed of repetitive tapping movement, diadochokinesis, walking speed, etc.). The correlation between 'squeeze' time and akinesia seen here may mean that in future it would be useful to include a test of isometric force production in the routine evaluation of akinesia.

Mechanisms Responsible for Increased Movement Times

The question arises as to whether the increase in movement times seen in the 'both together' task was produced by defects in the same mechanism that was responsible for the slowing seen in single movements. For example, it has been suggested that the amount of 'energy' available for a ballistic movement is limited in Parkinson's disease (see Hallett and Khoshbin, 1980). If this had to be distributed to many muscles, as in the simultaneous task, then this would result in further slowing of the individual movements. However, the idea that there is a strictly limited amount of 'energy' available in patients with Parkinson's disease probably is a simplification. Berardelli et al. (1986) have shown that the amount of EMG activity in a wrist flexion movement does not saturate, as expected if there were limited 'energy', but can be adjusted to the size of movement required. Furthermore, it would be expected that if there were a limited amount of 'energy', well-supported movements involving activity in the prime mover muscle alone, would be less affected than unsupported movements which involve additional activity in many postural muscles. This is not the case since the slowness of thumb movements is the same irrespective of whether the thumb phalanx is supported or not (Berardelli et al., 1984). Similarly, in the present study we have shown that if muscles involved in the 'squeeze' task are active for several seconds before the 'flex' then the speed of a superimposed flexion movement is not affected. Thus we conclude that simultaneous movements are not slow simply because more muscles are active at the same time.

How does the brain control the performance of two simultaneous movements? There are two possible mechanisms. 'Flex' and 'squeeze' or 'flex' and 'cut' may remain under control of independent programmes which are then run concurrently by the brain. Alternatively, a new, more complex programme might be formed which controls the simultaneous movement. Examples of complex programmes are known. They include handwriting, typing and sequential arm movements (Denier van der Gon and Thuring, 1965; Terzuolo and Viviani, 1980; Tuller et al., 1982; Carter and Shapiro, 1984) and are distinguished from linked or superimposed
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separate programmes by their ‘invariant characteristics’. In terms of space, this means that the speed of movement at one joint is linked closely with the speed of movement at a distant joint. In the temporal domain, the ratio of times taken to execute separate segments of a complex movement is always constant. Such constancy was not seen in the present experiments. In both normal subjects and patients, the separate movement times for ‘flex’ and ‘squeeze’ or ‘flex’ and ‘cut’ were not correlated in the ‘both together’ task. This suggests that the two components of the movements remained under the control of separate, but superimposed, motor programmes. It is our hypothesis that superimposition of two motor programmes represent an extra stage in the preparation of a movement. The pronounced slowness seen in the simultaneous movements of patients with Parkinson’s disease may then have two possible explanations: (1) there is a specific brain mechanism responsible for superimposing two programmes which is defective in Parkinson’s disease, or (2) addition of a new stage increases the number of interactions between various systems involved in preparation for a movement. The ability to cope with this increased ‘complexity’ of movement is compromised in Parkinson’s disease, leading to slowness in execution of the task.

In this context it was of interest that the combination of two similar isotonic ballistic movements (‘cut’ and ‘flex’) was less affected than the ‘squeeze’ and ‘flex’ task. It may turn out that the amount of motor disturbance in simultaneous movements strongly depends on the ‘complexity’ of the tasks involved and how different in nature they are (e.g., isometric versus isotonic; hold versus move; pursuit versus ballistic). Furthermore, the change in movement times is much smaller when the two tasks are performed with opposite limbs (‘flex’ and contralateral ‘squeeze’), requiring activity in the motor systems of both sides of the brain.

We suggest that the abnormality of striopallidal function, caused by nigrostriatal dopamine depletion in Parkinson’s disease, results in a defect in simultaneous processing of two different motor programmes in the same hemisphere. One of the major output targets of the basal ganglia is the supplementary motor area (SMA) (Jürgens, 1984) which is believed to have a role in the production of complex movements (Roland et al., 1980a, b; Tanji et al., 1980; Kurata and Tanji, 1985; Tanji and Kurata, 1985). In animals, SMA neurons show sustained activity following complex instructions which has been interpreted as reflecting the motor set of the animal (Tanji and Kurata, 1985). Although the role of the SMA in performance of concurrent movements has not been studied, it may have some role in the preparation of this type of complex movement, guided by basal ganglia input.

It may well be that the abnormalities seen in the present experiments contribute to the difficulties originally described by Schwab et al. (1954, 1959). Their tasks involved bilateral combination of two complex movements. We suggest that simultaneous performance of tasks much more difficult than those used here would lead to pronounced slowness even in the bilateral experiment. However, it must be emphasized that the principal observation of Schwab and colleagues was that patients did not perform their tasks simultaneously, as instructed, but preferred to
make sequential movements of first one task and then the other. It is not clear why the patients adopted this tactic. According to our findings, one possible explanation is that they believed that it was the best way to overcome slowness of movement that they knew would accompany simultaneous actions.

ACKNOWLEDGEMENTS

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