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Published paper

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On the Use of Low-Cost Computer Peripherals for the Assessment of Motor Dysfunction in Parkinson's Disease—Quantification of Bradykinesia Using Target Tracking Tasks

D. P. Allen, J. R. Playfer, N. M. Aly, P. Duffey, A. Heald, S. L. Smith, and D. M. Halliday

Abstract—The potential of computer games peripherals to measure the motor dysfunction in Parkinson's diseases is assessed. Of particular interest is the quantification of bradykinesia. Previous studies used modified or custom haptic interfaces, here an unmodified force feedback joystick and steering wheel are used with a laptop. During testing an on screen cursor moves in response to movements of the peripheral, the user has to track a continuously moving target (pursuit tracking), or move to a predetermined target (step tracking). All tasks use movement in the horizontal axis, allowing use of joystick or steering wheel. Two pursuit tracking tasks are evaluated, pseudo random movement, and a swept frequency task. Two step tracking tasks are evaluated, movement between two or between two of five fixed targets. Thirteen patients and five controls took part on a weekly basis. Patients were assessed for bradykinesia at each session using standard clinical measures. A range of quantitative measures was developed to allow comparison between and within patients and controls using analysis of variance (ANOVA). Both peripherals are capable of discriminating between controls and patients, and between patients with different levels of bradykinesia. Recommendations for test procedures and peripherals are given.

Index Terms—Bradykinesia, computer interfaces, Parkinson's disease.

I. INTRODUCTION

WITH the widespread availability of personal computers and low-cost peripherals, such as joysticks and steering wheels, the opportunity has arisen in recent years to adapt technology designed for the entertainments industry and develop low-cost measurement tools for use in clinical science and rehabilitation engineering. Possible applications in these fields are numerous and include the assessment of movement disorders such as Parkinson's disease (PD) and spasticity. In theory, the use of such equipment could remove some of the subjectivity

that is inevitably found whenever human judgement is involved and provide more objective patient assessments.

In this paper, we describe a pilot study to test the potential of low-cost games peripherals for the quantification of the motor dysfunctions associated with Parkinson's disease. In particular, we are concerned with the quantification of bradykinesia since this is generally accepted to be the most debilitating of the motor symptoms [1]. If the use of low-cost games peripherals were to prove successful, then assessment would not be limited to the clinic. Rather, the opportunity would arise to develop practicable home-based self-assessment systems for long term assessment. In the case of PD, this may be particularly useful for longitudinal monitoring of drug treatment.

The treatment of PD involves the careful management of medication. Since the presentation of PD can vary significantly between patients, the actual therapy prescribed is patient dependent and is often a case of balancing improvements to symptoms against possible side effects. For example, the most effective drug for relieving the motor symptoms of PD is levodopa, the side effects of which include end of dose "wearing-off" effects and dyskinesia. These tend to show three to five years after the start of treatment and can seriously affect the patient's quality of life [2]. The long-term effects of levodopa on PD progression are uncertain [3].

Current practice in the U.K. involves reviewing treatment in clinic on a three or four monthly basis at which time the effectiveness of the current medication is assessed and changed if necessary. Verbal feedback from the patient plays an important role in the assessment process. The severity of bradykinesia is often determined by observing the patient's performance during finger tapping tests. The degree of rigidity can be determined by the assessor passively bending the wrist or elbow, while any rest tremor present is self-evident. In clinical trials, a more thorough examination is obtained with the Unified Parkinson's Disease Rating Scale (UPDRS). However, Goetz *et al.* [4] showed that mastering the UPDRS is not easy and many practitioners fail at the first attempt. Even if assessments were free from subjective variation, clinical assessment would only provide a snapshot of the patient's symptoms at the time of assessment. In PD, the symptoms can vary considerably throughout the day depending on many factors including wearing-off effects, time since last meal and stress levels. With intervals of the order of months between clinical assessments the symptoms are effectively under-sampled in engineering terms. The increased frequency of home

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assessment, or community based assessment, between visits to the clinic afforded by the system described here might allow the clinician or nurse to make a more informed decision before changing medication.

This paper is arranged as follows. In the next section, a review of previous work is presented concerning instrumented measurement of some of the motor symptoms in PD. A description of the hardware and software development is then given followed by a description of the tracking tasks. Details of the participants are followed by the preliminary results. The paper concludes with a discussion of results and recommendations. Parts of the work have appeared in abstract form [5].

II. REVIEW OF PREVIOUS WORK

Several attempts have been made at instrumented measurement of rigidity and bradykinesia in PD with some success. In most cases reviewed below, however, the equipment used was either modified from off-the-shelf components or else custom-made, and not, therefore, readily available to the general public.

Prochazka *et al.* [6] used a force gauge to measure applied torque and a strain gauge to measure displacement in a system that mimicked the process of passive assessment of rigidity. The estimates of limb impedance obtained were well correlated with raters' UPDRS scores. This method was refined by Patrick *et al.* [7] to include a gyroscope on the wrist force gauge. Ghika *et al.* [8] developed a portable device to measure motor dysfunction capable of quantifying tremor, bradykinesia, and rigidity. Rigidity was determined passively using a goniometer and load cell arrangement, whereas bradykinesia was measured with custom-made test equipment designed to capture reaction times and movement speed. Dunnewold *et al.* [9] used a three-axis accelerometer to quantify bradykinesia, which correlated well with tap rate and movement time tests. They suggested that such a system would be suitable for longitudinal studies, as required in drug trials, for example.

Several groups have reported promising results using various forms of on-screen pursuit target tracking. Flowers [10] reported significant differences in tracking performance of PD patients compared to age-matched controls on a number of tests using a joystick connected to an oscilloscope. In one particular test involving sinusoidal tracking at increased frequencies, it was shown that patients' responses generally had higher root mean square (rms) errors than controls and that the breakdown frequency at which they became unable to track the target was lower. Flowers concluded that PD affects the ability to perform smooth continuous actions, as well as individual movements probably due to the fact that sufferers lack the ability to form an internal model of the movement prior to execution [10]. It was also noted that at the lower frequencies subjects were able to track the position of the target, while at the higher frequencies the mode of tracking changed to one of maintaining the same velocity as the target.

Flowers [10] employed two frequency ranges, a slow sweep from 0.17 to 0.50 Hz in 60 s and a two-stage fast sweep from 0.50 to 1.0 Hz in the first 35 s followed by 1.0 to 4.0 Hz in the next 35 s. By measuring rms errors and phase lags from these and other tests, it was shown that patients' tracking broke down at lower frequencies than controls (1.05 ± 0.37 Hz cf. $1.48 \pm$

0.59 Hz) and that patients generally were worse than controls at regular sinusoidal tracking. Above 1.0 Hz patients generally scored no better than they would have done by holding the joystick still. One of the characteristics of tracker motion reported by Flowers [10] during swept frequency pursuit tracking was that patients and controls tended to reduce the amplitude of motion in an attempt to reduce errors. In addition, patients also tended to lose synchrony at a lower frequency than the controls.

Hufschmidt *et al.* [11] used a potentiometer connected to a computer to show a reduction in tracking gain and increased lag by PD patients compared with controls. The tracking tasks involved the subjects rotating the potentiometer to match the sequence of illumination of one bank of LEDs with that on another computer-controlled bank. It was shown that PD patients generally showed more hesitation in making movements and that amplitude rather than velocity was the limiting factor for patients. Hacısalihzade *et al.* [12] had previously used a similar system with the addition of a torque motor to introduce disturbances to the potentiometer shaft.

Jones *et al.* [13] described a battery of pursuit and step tracking tasks for neurological examination using a steering wheel and computer arrangement. Abdel-Malek *et al.* [14] claimed that an ARMA model derived from tracking data was capable of quantifying the motor deficiencies of PD.

A home-based system for assessment of PD symptoms that consisted of a handheld transducer to measure thumb movement was developed by Sauermaun *et al.* [15]. The transducer was a modified speed controller from a model racing car, which required an additional analogue-to-digital converter to interface with a PC. Although this system did not use pursuit tracking, some of the parameters used for patient assessment gave comparable results to those used in tracking. It was shown that the total movement, the amount of hesitation and the frequency of operation were all lower in patients than controls and correlated well with UPDRS scores.

The BRAIN TEST developed by Giovannoni *et al.* [16] involved patients tapping two keys at either side of a standard keyboard in a similar manner to the clinical testing of bradykinesia with tap tests. Recording the total key presses in a fixed period provided a measure of bradykinesia, while the cumulative time the keys were depressed longer than 17 ms was used to indicate the presence of akinesia, i.e., poverty of movement. The variance in intervals between consecutive keystrokes gave a measure of rhythmicity that was used to imply the level of incoordination. It was claimed that such measures could be used in home-based longitudinal monitoring of symptoms. The utility of tapping tests for longitudinal studies, however, has been questioned by Kraus *et al.* [17] who concluded that more complex movements are required for quantifying dopaminergic response.

Spiral drawing tasks on PC-based digitising tablets have also been applied to the quantification of PD symptoms. However, their use in quantifying bradykinesia might be limited by the fact that bradykinesia is improved with the presence of visual cues [18]. In the drawing tasks, the spiral to be tracked is visible during the entire task, which is generally not the case in pursuit tracking.

Despite the fact that pursuit tracking has proved so successful for quantifying PD and other neurological symptoms, to the best

of our knowledge no one has produced an inexpensive, readily available system for general use. It is believed that the system described in the next section is the first to do so.

III. SYSTEM DESCRIPTION

To be accessible by the majority of people, the PD assessment system was designed to run on a Windows XP-based machine with a minimum of one USB port. A Windows-based application was developed complete with GUI that permits easy inputting of patient details and the selection of tracking tests via easy to read dialog boxes. During the pilot study, data analysis was performed offline using MATLAB Ver. 7. Ultimately, data analysis could be incorporated into a single compact application that provides graphical information for clinical use. The application was written in C++ using Microsoft Visual Studio .NET 2003. To interface with the peripherals, it is first necessary to install DirectX Ver. 9, for which access to the Internet is required. The application was successfully run on a laptop with a 1-GHz processor and 256 MB of RAM, this specification may give an indication of a minimal configuration required to undertake these tests.

In this study two commercial games peripherals were tested, a Saitek Cyborg Evo Force joystick and a Saitek R440 Force Wheel steering wheel. Both devices permit force feedback, which could be used to oppose the force generated by the participants. However, this facility was not used in this study. The joystick had a handle length of approximately 20 cm and a deflection from center of $\sim \pm 7.5$ cm, giving an angle of deflection $\sim \pm 20^\circ$. The wheel had a diameter of 20 cm at the center of the rim and a deflection of $\pm 90^\circ$, giving a total circular movement of ± 175 cm. It can be seen, therefore, that of the two devices, the joystick had the higher gain.

Depending on which peripheral was selected, the on-screen position of a 10-mm black cross was controlled by either the rotation of the steering wheel or the displacement in the x axis of the joystick. The movement of the stick or wheel was stimulus-response compatible, i.e., movement to the left (right) corresponded to a proportional left-shift (right-shift) in tracker position. Both peripherals were calibrated such that at the midposition the tracker was located at the center of screen, and at maximum displacement the tracker was positioned at either edge of the window. The screen refresh rate and the sampling rate of the peripherals' position was 62.5 Hz, which satisfied the Nyquist rate since the highest expected frequency of motion was the 5 Hz normally associated with PD tremor. The sampling rate of 62.5 Hz resulted from down-sampling by a factor of 2 the 125 Hz sampling rate returned by the DirectX drivers. This down-sampling was used to avoid unnecessary screen updates, and reduce the quantity of data generated. A step-like motion was initially observed when tracking with the joystick instead of the continuous motion required for fine control. The average step size measured approximately 1% of total displacement, which implies 7-bit position discretization. (The manufacturer's specification was not available to verify this). To smooth this stepping motion and in so-doing give the system a less jerky feel, a low-pass filter was applied to the raw joystick position data. It was found empirically that a fourth-order Type II Chebyshev filter with 40-dB stop band

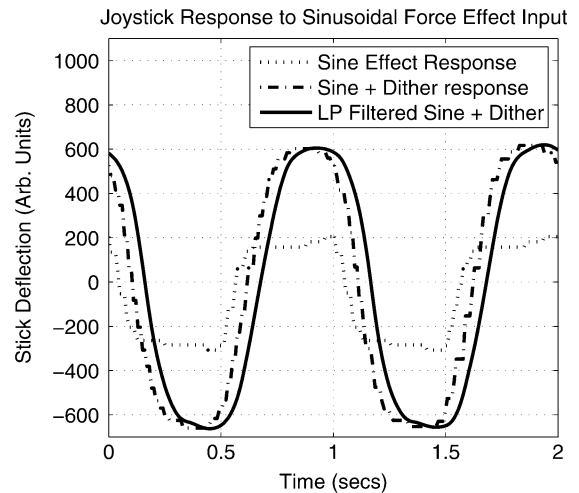


Fig. 1. Plots showing the hysteresis exhibited by the joystick when driven by a 1 Hz sine wave force effect (. . .) generated by the host PC. With the addition of a 50 Hz dither signal, the amount of hysteresis is greatly reduced (. - . - .). Solid curve is the low-pass filtered response to the 1 Hz and dither signal combination.

ripple and a cutoff frequency of $\pi/8$ (~ 3.9 Hz) provided the best compromise between smooth tracking and system lag. An advantage of using such a low cutoff frequency is that any hand tremor the patient might have would be attenuated. In the case of the steering wheel, the same step size of $\sim 1\%$ did not cause any significant problems with the controllability of the system, probably due to the lower system gain between wheel displacement and tracker position, which meant that LP-filtering was not necessary in this case.

Two other problems encountered with the joystick were the hysteresis associated with the servomotors' gears and the "stiction" found at the center position. Because of these, a non-linear force was required to move the handle, making fine control around the center position difficult. A common method of dealing with this type of nonlinearity is the use of a high-frequency dither signal applied to the actuating motors, which effectively linearises the system's describing function [19]. In the case of the joystick used in this study, the dither signal was applied to the force feedback motors by downloading appropriate computer-generated sinusoidal force effects. An experiment designed to show the effects of hysteresis by driving the force feedback servomotors with a low frequency sinusoid (~ 1 Hz) and recording the stick position resulted in the stick moving with the clipped response characteristics typical of geartrain-induced hysteresis, as shown in Fig. 1. By superimposing a high-frequency (~ 50 Hz) dither onto the low-frequency drive signal, it can be seen in Fig. 1 how hysteresis was eliminated. The use of such a high-frequency dither beyond the band limit of the joystick did not result in any detectable movement of the handle and so did not introduce any signal artefact. In all the tracking tasks reported here, a 50-Hz sinusoidal dither signal was applied to the joystick's feedback servos. In contrast to the joystick, the steering wheel did not exhibit any noticeable hysteresis or "stiction," and, therefore, did not require the addition of a dither signal.

The tracking area within the application's client window had a horizontal length of 1024 pixels and was divided into

500 equal steps centred on zero and ranged from -249 on the left edge to $+250$ on the right. The physical size of the application's window on the development laptop described above measured 262 mm on the horizontal axis by 190 mm on the vertical. The tracking tasks described below were designed with respect to the 500 divisions of the window, so that a displacement in amplitude of $+100$ meant 100 steps right of the center, whereas a -100 displacement was interpreted as 100 steps to the left. Using the above measurements a displacement of 100, for example, represented a physical movement of approximately 100 mm.

When performing tests, the subjects were seated in front of the computer approximately 90 cm from the screen. At this distance, the angle subtended by the tracker horizontally was $\sim 17^\circ$. When using the joystick subjects were directed to keep the elbow of the tracking hand on the table throughout testing. There were no such restrictions in the case of the steering wheel, which was positioned directly in front of the screen. The steering wheel was gripped in the three o'clock position for right-handed tracking and nine o'clock for the left hand.

IV. TRACKING TASK DESCRIPTION

Tests were developed in conjunction with clinicians from the Royal Liverpool University Hospital, Liverpool, U.K., at the PD specialist clinic held weekly at Broadgreen University Hospital, Liverpool. Prototype trials were undertaken with patients attending the clinic, with informed consent and local ethical committee approval. In each session, participants undertook two pursuit tracking tasks and two step tracking tasks (Tests 1–4, described below). The test battery was performed firstly with the joystick and then repeated with the steering wheel. All participants also performed two other tests. The first was to ensure that participants were capable of activating the peripheral buttons, and used a firing task at the start of each session to count the number of times the button or trigger was operated in a 10 s period. The second additional test was the tapping test used at York District Hospital, York, U.K., to determine the degree of bradykinesia, in which patients seated at a table alternately tap two markers placed 30 cm apart for 30 s. Tests were carried out weekly on the same day, in the same order each week. Participants were allowed to rest for as long as they wanted between each test, and began each test in their own time. In addition, PD patients were assessed at the beginning of each session by one of the authors (DPA) and assigned a UPDRS score for rest tremor, bradykinesia, and rigidity.

A. Pursuit Tracking—Test 1

In both pursuit tracking tasks, a green-colored circular target on a white background moved horizontally across the client window with the subjects attempting to maintain the tracker's position on the target as best as they could. Both target and tracker were restricted to displacement in the horizontal or x axis. The target measured approximately 12 mm in diameter on the system described above, which represented about 4.5% of the tracking window's width.

In the first pursuit tracking task, the target moved in a pseudo-random manner determined by the sum of 10 sine waves and had an approximate duration of 45 s. This number of sine waves

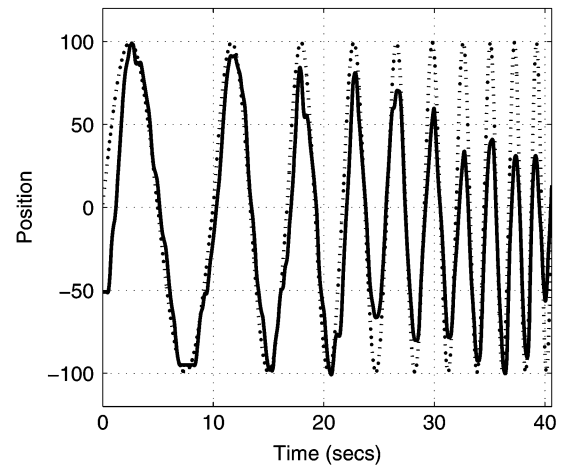


Fig. 2. Plot of target displacement against time (dotted line) for the swept frequency pursuit tracking task with the right hand. Displacement of target and tracker in the x direction is shown on the vertical axis. Subsequent data analysis was performed on the last nine cycles to avoid transient effects on the first cycle. Solid line is an example of a patient's performance with the steering wheel (Bradykinesia = 3). Note that the tracking range decreases with increasing target frequency and that movement is restricted to negative displacements, i.e., the left-hand side of the screen indicating that this patient had difficulty in turning the wheel away from the body.

was sufficient to give the impression of random movement to participants. The 10 sine waves for the right-handed tracking task had frequencies of (1.00, 1.83, 0.47, 1.67, 0.04, 4.08, 0.13, 2.12, 0.17, 3.38 Hz) and amplitudes of (100.0, -25.8, 9.0, -11.3, -52.5, -65.3, 17.5, 19.4, -48.5, -13.8), respectively. These values were selected from a randomly generated set to give a propitious range of target movement and velocity. The amplitudes are given with respect to the number of steps in the horizontal axis as described above. In the case of the left-handed tracking task, the polarities were reversed. This ensured that the amount of movement away from and towards the body was the same for each hand. This test was used only as a screening process to determine the subjects' ability to use the system.

B. Pursuit Tracking—Test 2

In the second pursuit tracking task, based on the method described by Flowers [10], the target's frequency was swept incrementally from low to high frequency in the horizontal axis. We employed a frequency range of 0.1–0.6 Hz, swept incrementally in 10 equal steps, completing one full cycle at each increment, as shown in Fig. 2. The duration of this test was 41 s. It was anticipated that if the deficiencies in tracking were apparent at these lower frequencies and if they were in fact due to the motor symptoms of PD, then it may be possible to develop measures to quantify those symptoms. The dimensions and colors of the tracker and target were the same as those in the first tracking task. In both of the pursuit tracking tasks, participants received feedback on their performance in the form of a score representing the percentage of the total time that the tracker was positioned within the target.

Using one of the parameters of Flowers [10], the measure of tracking performance for the swept frequency pursuit tracking was the amplitude, or more precisely, the range of tracker movement. The range of movement was obtained for each cycle of

the frequency sweep and normalized by dividing by the target range. A score of 1 for a given cycle, therefore, represented a range of tracker movement equal to that of the target, whereas a score greater or lower than 1 was obtained if the range of tracker movement was higher or lower than the target's range, respectively. The first cycle (0.1 Hz) was not used in the analysis since transient effects caused by starting the test with the peripheral held off center, for example, could bias the score for this cycle.

C. Step Tracking—Test 3

The first step tracking task involved positioning the tracker alternately between two fixed points on the screen as quickly and as accurately as possible for a period of 30 s. This test was designed to mimic the tapping exercises performed in the clinical assessment and in a manner similar to the BRAIN TEST of Giovannoni [16]. In our test, the fixed points took the form of 12 mm squares set 300 steps (182 mm) apart, equidistant from the client window center. At any time one of the squares would be colored green, the other red. Participants were requested to move the tracker to the red square as quickly as possible at which point the colors reversed and the process repeated. The visual clues provided by alternating the colors to indicate when the target had been reached were included to prevent undershoot and help reduce overshoot leaving the participants free to concentrate on speed of movement. A score that counted the number of color changes gave feedback on performance. Penalties were not awarded directly for any overshoot or undershoot of the target, but inaccurate tracking meant a potentially lower number of repetitions in the fixed period of the test. Tactically, it would be in a participant's best interest to aim at the square and not go beyond it.

D. Step Tracking—Test 4

In this step tracking task, the complexity was increased by the addition of three extra squares equally spaced along the x axis between the original two. One of the squares, selected randomly, was set to red with the remainder green. Again the goal was to head for the red square, but with the added condition that once over the target participants were required to pull the trigger of the joystick or press a button on the steering wheel to increment the score and activate the next target. This, therefore, tested their ability to move accurately and quickly and included an element of coordination not present in the previous tasks. The duration of the test was 60 s.

When considering tracking tasks, it is often useful to determine the index of difficulty (ID) as defined by Fitts' law [21]. The minimum ID for this particular test was obtained if the next target was adjacent to the current target and equalled 3. The maximum ID equalled 5 and occurred when the next and current targets were the two extreme squares.

With this particular test, however, there was the potential problem of color blind individuals not being able to recognize the current target. In the first step tracking task, this was not considered a problem since subjects merely had to alternate between the squares, and eventually would hit the right target. Although none of the subjects tested during the pilot study were

color blind, it was possible to change to another set of colors if needed.

A number of measures can be made from this test including initial movement time to next target, time to acquire target, reaction time from target changes to participants' movement and target overshoot. The rationale for this particular test has been supported by previous work. It was reported by Zappia *et al.* [22] that, with a bank of switches and randomly illuminated lights, measures of movement time, and reaction time were prolonged in PD. Furthermore, they suggested that movement time rather reaction time was correlated with bradykinesia and could be useful, therefore, in longitudinal studies of drug efficacy. Sheridan *et al.* [23] also showed that movement times rather than reaction times were significantly differently in patients than controls.

V. PARTICIPANTS

A. Patients

The series of test reported here were undertaken on a weekly basis by 13 patients with idiopathic PD (mean age 62.8 ± 8.8 years). The group consisted of eight males and five females recruited from the Neurosciences Department at York District Hospital and from the York branch of the Parkinson's Disease Society. Each gave their informed consent. No one was under any commitment to complete the tests once started and could withdraw their cooperation at any time. Patients were tested at the same time every week and were asked to take their regular medication at the normal time before attending. However, not all participated in every session for a variety of reasons including other commitments or illness. The results tables (described below) indicate the number of sessions completed for each test. All patients were right handed, some were PC-literate but none had significant previous experience of computer games peripherals. A summary of the patients' ages and illness duration is given in Table I. Also listed are the patients' typical symptoms, which varied to a greater or lesser extent throughout this study; it was conceivable that a patient who did not exhibit bradykinesia in one session, for example, could show some in another and vice versa.

B. Controls

A total of five right-handed controls (mean age 55.8 ± 9.4 years) undertook the series of tests on a similar basis to the patients, i.e., on the same day of the week at approximately the same time of day. To ensure better age matching with patient group, no controls under the age of 50 were recruited to the study. One of the authors who was under the age of 50 did act as a control. The group comprised patients' partners or helpers and volunteers from the University of York. Although most were PC-literate, none had previous experience with computer gaming peripherals. Our aim was to determine if quantitative analysis from longitudinal studies with a small control group were sufficiently reliable to allow discrimination between controls and patients. In total 13 sessions from the five controls were undertaken.

TABLE I
PATIENT DETAILS

Patient ID	Age	Years diagnosed	Symptoms		Sessions attended
			RH	LH	
1	39	1	T,R,B	-	2
2	63	4	-	B	4
3	73	8	-	-	6
4	63	8	-	-	6
5	69	2	-	R	4
6	62	6	-	R	6
7	71	10	T,R	R	5
8	70	3	R	R	7
9	68	5	R,B	R,B	6
10	60	3	T,R,B	-	5
11	58	7	T,R,B	-	4
12	57	2	-	R,B	7
13	64	8	R,B	R,B	7

Details of the Parkinson's patients showing the symptoms present in either arm. Key: T = tremor, B = bradykinesia, R = rigidity. Right column indicates the number of testing session completed by each patient.

TABLE II
RANGE SCORE FOR SWEEPED FREQUENCY PURSUIT TRACKING TASK

Hand	Bradykinesia UPDRS Score					
	Controls	0	1	2	3	4
RH	1.22	0.88	0.77	0.47	0.68	0.27
	Joystick	0.18	0.36	0.33	0.44	0.45
LH	1.25	0.94	0.83	0.88	0.87	0.75
	Joystick	0.20	0.35	0.40	0.52	0.21
RH	13	63	41	8	3	8
	Steering	0.92	0.76	0.80	0.55	0.53
Wheel	0.11	0.21	0.31	0.45	0.24	0
	13	29	16	4	14	1
LH	1.00	0.82	0.66	0.66	0.65	0.54
	Steering	0.16	0.26	0.32	0.24	0.19
Wheel	13	32	18	7	3	4

Mean (first entry), standard deviation (second entry) and number of testing sessions (third entry) of range score for cycle 10 of the swept frequency pursuit tracking task for each of the groups in Fig. 3. The discrepancy between the numbers of patient sessions with the joystick and steering wheel are due to the joystick tests being developed earlier in the project.

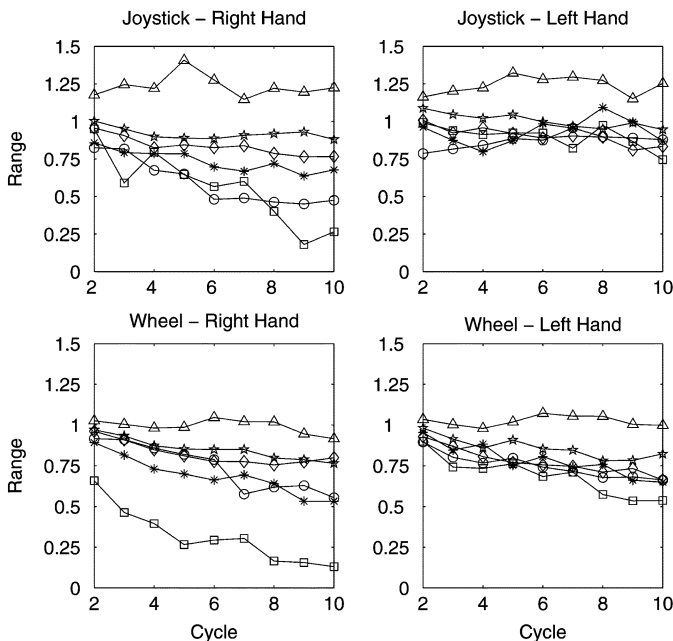


Fig. 3. Mean range score at each cycle for controls and bradykinesia groups on the swept frequency pursuit tracking tasks. Key to symbols: * UPDRS (bradykinesia) 0; \diamond UPDRS 1; \circ UPDRS 2; * UPDRS 3; \square UPDRS 4; \triangle Control.

VI. RESULTS

A. Pursuit Tracking—Test 1

The pseudo-random tracking test was used only as an initial screening process to determine the subjects' ability to use the system. No quantitative analysis of the data was undertaken.

B. Pursuit Tracking—Test 2

The mean score for each cycle obtained by the controls and each of the bradykinesia groups is shown in Fig. 3 for both peripherals. It can be seen that for both peripherals using either hand that the mean scores for the controls was higher than that of the patients at each cycle. Generally, the more severe the bradykinesia, then the lower the mean score attained. The exception being the response with the left hand using the joystick

in which the plots from the different bradykinesia groups are less distinguishable. It is also noticeable in Fig. 3 how the range of movement in all cases tends to reduce as the frequency increases. The means and standard deviations across the groups for cycle 10 are given in Table II. One-way analysis of variance (ANOVA) applied to the results shows that the mean value of each patient group and the controls is significantly different for both peripherals, $P < 0.01$ for the right hand and $P < 0.01$ for the left. However, if the patients groups are considered without the controls, then for the right hand with both devices $P < 0.01$, while for the left hand the mean scores are not significantly different, $P > 0.05$. This suggests that, while this test is capable of differentiating between patients and controls, with the left hand it is not capable of distinguishing between patient groups meaning that the test score obtained is not dependent on the severity of bradykinesia.

C. Step Tracking—Test 3

The test scores from the first step tracking test (consisting of two squares) plotted against bradykinesia UPDRS score for all patients and controls are shown in Fig. 4. Mean scores for either hand with each peripheral are given in Table III. One-way ANOVA revealed that the mean scores of patients and controls were significantly different, $P < 0.01$, for both peripherals. The mean scores of patient groups were also significantly different, $P < 0.05$, which implies that this test is capable of differentiating between patient groups.

Since this test was based on the tapping tests performed in clinic, it is interesting to note the degree of correlation between the test scores and the number of taps from the same session. The overall correlation between tap rates and tracking scores with the joystick was $r = 0.41$ and $r = 0.44$ for the right and left hands, respectively. Similarly, $r = 0.45$ and $r = 0.45$ with the wheel.

D. Step Tracking—Test 4

In the second of the step tracking tasks, the additional requirement imposed on participants was to position the tracker over the target before activating the appropriate firing button or

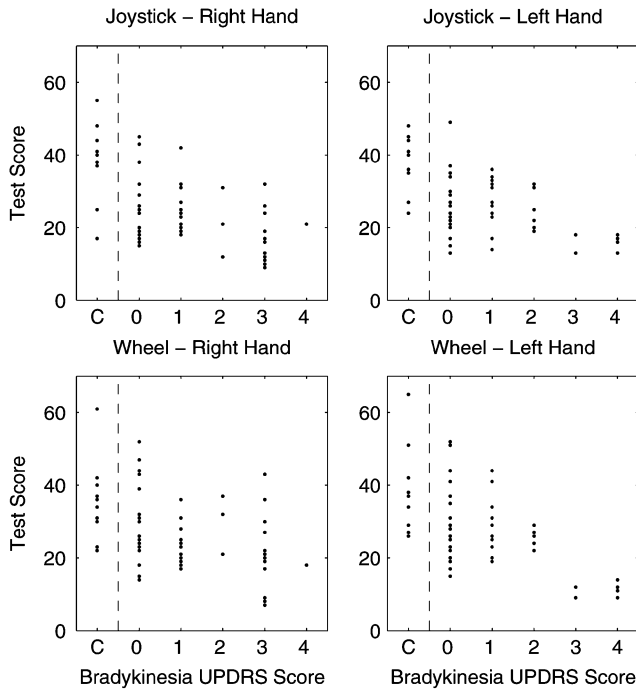


Fig. 4. Test scores from the first of the step tracking tasks involving two squares. Patients are grouped according to UPDRS bradykinesia score determined at the start of each session. Scores from the control group appear to the left of the vertical line.

TABLE III
SCORES FOR THE FIRST STEP TRACKING TASK

Hand	Bradykinesia UPDRS Score					
	Controls	0	1	2	3	4
RH	38.1	24.4	24.8	21.3	15.1	21.0
Joystick	10.2	9.0	6.5	9.5	7.2	0
	13	21	14	3	15	1
LH	37.8	25.9	26.2	24.8	15.5	15.5
Joystick	7.3	7.8	7.3	5.6	3.5	2.1
	13	28	12	6	2	6
RH	35.2	28.6	23.7	30.0	18.7	18.0
Steering	10.6	10.9	5.6	8.2	11.3	0
Wheel	13	21	14	3	15	1
LH	38.9	28.2	29.7	25.8	10.5	11.5
Steering	11.3	9.4	8.6	2.4	2.1	1.6
Wheel	13	28	12	6	2	6

Mean (first entry), standard deviation (second entry) and number of testing sessions (third entry) for for the first step tracking task for each of the groups in Fig. 4 averaged over all sessions.

trigger. The mean scores for controls and each of the patient groups are given in Table IV. One-way ANOVA revealed that the mean scores of all patient groups and controls were significantly different for both hands when using the steering wheel, $P < 0.01$. This was also the case for the right hand with the joystick, $P < 0.01$, whereas with the left hand the mean scores were not significantly different, $P > 0.05$. If the patient groups are considered without the controls, then the mean scores with the joystick were not significantly different with either hand, $P > 0.05$. However, with the steering wheel the mean score of either hand was significantly different, $P < 0.01$. These results suggest that with the steering wheel scores from this tracking

TABLE IV
SCORES FOR THE SECOND STEP TRACKING TASK

Hand	Bradykinesia UPDRS Score					
	Controls	0	1	2	3	4
RH	30.00	26.08	22.07	19.00	21.50	18.00
Joystick	5.31	5.12	6.60	1.41	7.48	0
	13	24	15	2	12	1
LH	28.45	27.25	25.88	23.57	28.00	25.00
Joystick	3.67	4.92	5.63	6.65	1.41	3.74
	13	24	17	7	2	4
RH	44.91	38.33	33.47	23.50	27.42	17.00
Steering	4.13	6.08	6.76	16.26	11.29	0
Wheel	13	24	15	2	12	1
LH	45.45	39.25	31.53	33.00	38.00	30.50
Steering	4.84	4.76	5.94	5.88	0	5.20
Wheel	13	24	17	7	2	4

Mean (first entry), standard deviation (second entry) and number of testing sessions (third entry) for the second step tracking task for each of the groups in Fig.5 averaged over all sessions.

test are dependent on bradykinesia, but this is not necessarily the case with the joystick.

In terms of correlation between scores and tap rates, then subjects did not perform as well with the joystick as with the wheel. The overall correlation coefficients for the joystick were $r = 0.47$ for the right hand and $r = 0.12$ for the left. With the steering wheel these were $r = 0.67$ and $r = 0.56$.

VII. DISCUSSION

In the course of this work we have attempted to test the usefulness of two off-the-shelf PC peripherals for the assessment of bradykinesia in the upper limbs. A number of on-screen pursuit and step tracking tasks have been implemented and a comparison of results made. These tests were based on other, reasonably successful tests found in the literature and modified to suit the purposes of this study.

In most PD cases, the initial presentation of symptoms including bradykinesia occurs unilaterally. Therefore, it is conceivable that by limiting the testing to the dominant hand, the presence of bradykinesia might be undetected. By including tests of both the dominant and nondominant hands, we have extended the scope of previous work [10] to allow assessment of the majority of PD patients. However, in certain cases, especially in the early stages of the disease, bradykinesia is not necessarily observed in the upper limbs despite being present elsewhere in the body. Clearly, a system for assessment like the one developed here would be of little use in such cases.

With the relatively low number of subjects used in this pilot study, a statistical analysis of the results could be misleading. However, several of the test results have highlighted qualitative differences in the performance of controls and the UPDRS-rated patients, which has been corroborated by ANOVA. In addition to the small sample size, artefacts in the data are likely to be present due to the subjectivity of the UPDRS scores determined by a single rater and possibly to the actual subset of UPDRS motor function tests selected. A more controlled procedure would involve a fuller UPDRS test performed by several practitioners, along with a comparison with other clinical measures such as the nine hole peg test.

A number of issues have been raised during the course of the development and testing of the prototype system. These have included the actual format and parameters of the tracking tasks.

The pseudo-random tracking task was intended as an initial screen to determine the subjects' ability to operate the system. In practice, only patients that showed signs of dementia or other cognitive impairment performed so badly that they were excluded from the pilot study. Those that did take part provided vital feedback during the development of the testing procedure and on the usability of the equipment. While a home-based system would clearly be aimed at those competent enough to use a PC, this limitation would not apply in clinic where assistance would be at hand for those requiring it. The highest frequency component of the pseudo-random tracking signal at ~ 4 Hz is greater than the 0.7–2.0 Hz suggested by Neilson *et al.* [20] as the limit of tracking by eye movement alone. Tracking above this frequency band implies the use of adaptive neural strategies involving the generation of an internal model. Flowers [10] has hypothesised that PD patients lack the ability to form these internal models, which suggests that the degree of bradykinesia is not the only factor that can affect tracking performance. The frequencies chosen are also below the range of 4–6 Hz normally associated with Parkinsonian tremor. The tracking performance of patients and controls was similar irrespective of the patients' symptoms, and, therefore, could not be used to determine the degree of bradykinesia. However, this test was retained in subsequent sessions to help with familiarization of the equipment.

Although not shown in the results, it is also interesting to note how the peripherals compared on the pseudo-random test, with the steering wheel scoring better than the joystick. Verbal feedback from the participants suggested that the higher gain and phase lag of the joystick meant that responding to the random element of the task was more difficult than with the wheel. Another interesting observation made during the pseudo-random tracking task was that subjects often felt that the test had been made harder than in previous weeks when in fact it had remained the same. At the start of each test, participants were informed that the target would change direction randomly, which most believed.

In the second of the pursuit tracking tasks in which the target frequency increased incrementally, the results were encouraging. Since one of our goals was to monitor patients in the long term, it was decided to use a frequency range below the breakdown frequency of 1.0 Hz reported in [10]. This ensured that patients had a realistic chance of finishing the test and did not become dismayed by continually performing badly, which may happen if the task was too demanding. The mean range scores at each cycle tended to decrease with increasing bradykinesia score, as shown in Fig. 3. As expected, this became more apparent as the frequency was increased. The separation between the various groups towards the end of the sweep at the ninth and tenth cycles generally corresponds to bradykinesia rating. This is especially noticeable with either hand using the steering wheel, where the low gain of the device hinders rapid movement, and is more problematic for the worse afflicted patients. At the higher frequencies, the high gain of the joystick was expected to help participants maintain the target velocity tracking. With the right hand, the mean ranges tended to be

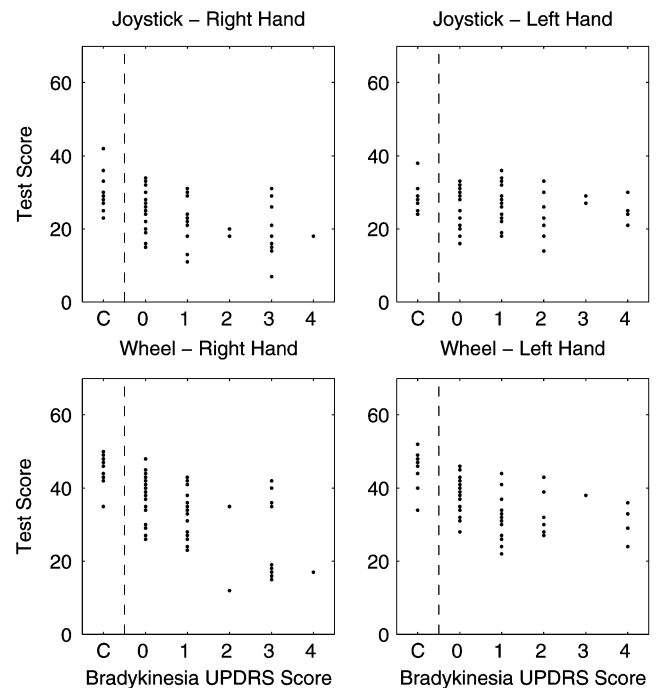


Fig. 5. Test scores from the second of the step tracking tasks involving five squares. Patients are grouped according to UPDRS bradykinesia score determined at the start of each session. Scores from the control group appear to the left of the vertical line.

separated more than with the steering wheel. However, with the left hand the mean plots appear reasonable similar irrespective of the severity of symptoms. Why this should happen is unclear, but several subjects stated that because control with the joystick was difficult, they tended to concentrate more when using the left, i.e., less dominant hand than with the right. In summary, frequency sweep tracking with either peripheral results in qualitative differences in performance between groups, but ANOVA revealed that the score from this test is not dependent on the severity of bradykinesia.

The first of the step tracking tasks involving two squares was based on the tap tests performed in clinic. The scores in Table III and Fig. 4 indicate that mean tracking rate generally decreases with increased bradykinesia and is more noticeable in the left hand. There appears to be no discernable advantage when using one peripheral over the other in this task. The fact that precise aiming was not required meant that the higher gain of the joystick resulted in faster movement between targets, but at the expense of overshoot; whereas the lower gain of the wheel resulted in higher tracking accuracy with less overshoot. It is interesting to note that these opposing strategies resulted in similar scores.

In the second of the step tracking tasks involving a randomly selected target from a bank of five, the goal was to position the tracker over the current target and fire. Previous studies involving aiming tests have shown that movement time rather than reaction time is affected by PD [22], [23]. In this pilot study, we have considered the total time by combining reaction and movement times and compared this to the degree of bradykinesia. The mean time taken to acquire targets has been estimated by counting the number of successful acquisitions achieved during a 60 s period. Fig. 5 and Table IV show that the mean score tends

TABLE V
SUMMARY OF TEST RESULTS

	Task		
	Sweep Pursuit	1 st Step Test	2 nd Step Test
Peripheral	✓	✓✓	✗
Joystick	✓	✓✓	✗
Steering wheel	✓	✓✓	✓✓

Summary of test results based on one-way ANOVA. Key: ✗ inconclusive - cannot differentiate between controls and patients ($p > 0.05$), ✓ capable of differentiating between controls and patients ($p < 0.05$), ✓✓ capable of differentiating between controls and patients with different levels of bradykinesia ($p < 0.05$).

to decrease with increasing severity of bradykinesia. The differences in score between the least and most affected were greater with the steering wheel than with the joystick. In general, scores were lower in this test with the joystick than with the wheel, which was not the case in the first step tracking test. According to feedback from subjects during the testing, this discrepancy was due to the relative difficulty subjects had in positioning the tracker over the target because of the joystick's higher gain and phase lag. The ANOVA results showed that the scores from the steering wheel were dependent on bradykinesia severity, which was not the case with joystick.

A summary of the above tests in the form of recommendations for test procedures and peripherals is given in Table V.

While this pilot study has shown promising early results for the developed system, caution should be taken in interpreting the results. In addition to the slowness in programming and execution of movement in PD, Berardelli *et al.* [24] list five secondary causes that potentially contribute to bradykinesia; they are, muscle weakness, rigidity, tremor, movement variability, and bradyphrenia or slowness of thought. However, they further stated that the evidence linking these secondary causes to bradykinesia is not clear. In light of this, we assumed that deficits in tracking performance were due to bradykinesia alone. If these additional factors are relevant though, it is difficult to envisage how simple tracking tasks could achieve a consistent and reliable measure of bradykinesia. In fact, during this pilot study, some of the patients tested exhibited signs of muscle rigidity with and without the presence of bradykinesia. It is not clear how this affected performance. It is possible that the other factors significantly contribute to tracking performance, and that what is being measured is actually a degree of overall slowness. While this in itself might be useful, it would not fulfil the requirements of a drug management tool since symptoms respond differently to different drugs. To assess the system more fully, multicenter long-term trials involving subjects with a wider range of symptoms would be required.

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