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Analysis of finger-tapping movement

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Abstract

The piano-playing-like finger-tapping movement has been analyzed with a precision image-based motion analyzer (PRIMAS). 32 healthy subjects (148 recordings) and 10 Parkinsonian patients (25 recordings) were tested. The tracking of fingers during the whole movement increased the level of information obtained from the finger-tapping test compared to visual observation or to measurement with simple contact sensors. Different feature extraction methods have been developed to evaluate the movement and thus the actual performance of the tested person. The reliability of a novel parameter, the finger-tapping test score (FTTS), that takes into account both the speed and the regularity (periodicity) of finger-tapping, was assessed in six control subjects, with four subjects tested at least 14 times. FTTS helps in staging of Parkinsonian patients. A simple and cheap device (passive marker-based analyser of movement, PAM) has been developed that is affordable for routine clinical use.

Keywords: Tapping test; Movement analysis; Finger movement; Finger-tapping test score

1. Introduction

The tapping test has been applied to assess the accessory muscular control and motor ability as early as the 19th century. Hollingworth (1914) reports an experiment on female subjects using an electric counter to characterise the influence of menstruation, and since then tapping tests have been widely used for quantification of ataxia (Notermans et al., 1994), assessment of patients recovering from acute stroke (Heller et al., 1987), testing of patients with alcoholic Korsakoff's syndrome (Welch et al., 1997), quantification of Alzheimer's disease (Ott et al., 1995), and characterisation of the upper limb motor function (Giovannoni et al., 1999). Horton (1999) found that subjects with higher intelligence had better neuropsychological test score performances except for the finger-tapping with the dominant hand test. Dash and Telles (1999) used the finger-tapping test to assess motor speed: there was a significant increase in performance following 10 days of yoga in children and 30 days of yoga in adults. Volkow et al. (1998) found a strong correlation between dopamine D2 receptors and the motor task characterized by the finger-tapping test. Quantifying impairments in Parkinson's disease, however, is difficult (Rao et al., 2003), and Muir et al. (1995) and Jobbágy et al. (1997) used the tapping test to estimate the severity of motor symptoms in this disease.

In clinical practice, the finger-tapping movement is very often evaluated visually, thus resulting in a coarse resolution. Simple contact sensors are reported to help objective assessment (Muir et al., 1995). There are many versions of the upper limb tapping test: hand-tapping, finger-tapping with one or more fingers, single hand, both hands, with or without a scheduler signal, etc. The feature extraction methods currently used for the tapping tests do not always provide measures which are useful in rehabilitation or in medication. Heller et al. (1987) report that measurement of the finger-tapping rate was not useful in testing stroke patients; only the Frenchay Arm Test, the Nine Hole Peg Test and grip strength measurement could be used to record the recovery curves of patients. Shimoyama et al. (1990) found

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that only the time-sequential histogram of tapping intervals could distinguish between the motor dysfunctions studied. Acreneaux et al. (1997) report that "hand to thigh tapping", "table tapping" and "finger-tapping to adjacent thumb" quantify the performance of the tested subjects differently.

The aim of this study was to provide a detailed analysis of the piano-playing-like finger-tapping movement using a system to track the fingers during the whole movement.

2. Materials and methods

2.1. Subjects

Ten Parkinsonian patients and 32 control subjects were tested. Altogether 25 recordings were made from Parkinsonians and 148 recordings from healthy subjects. Parkinsonian patients (six male and four female, aged between 45 and 78, mean: 66.9, standard deviation 8.5) were scored according to the Hoehn–Yahr scale by expert neurologists (Table 1).

The control group comprised 21 young (under 27) and 11 senior (over 50) citizens (see data in Table 2). Some of the healthy subjects had experience in routinely performing coordinated hand or finger movements, i.e. playing the piano or doing free-hand drawing: they will be referred to as "experienced" subjects. Both healthy subjects and patients gave written consent before being enrolled in this study.

2.2. Apparatus

Neurologists usually evaluate the finger-tapping test by visually estimating the speed and regularity of the movements. However, if a device is able to determine the position of the fingers during the whole test, then automated evaluation is possible using algorithms of different complexity.

Table 2
Young and senior subjects tested

	Age		Gender: male/all	Handedness right/all	Experienced
	Mean	S.D.			
Young	23	2.2	19/21	17/21	5/21
Senior	54.2	3.7	10/11	10/11	1/11

Passive markers are attached to anatomical landmark points and the trajectories of the markers are determined. Passive markers are especially suitable for this task: they are lightweight (1 g each), the 9-mm diameter spheres can easily be attached to the phalanxes by elastic stripes, and no wires are needed between the markers and the analyzer. Passive markers cause no discomfort and do not alter the tested movement. Fig. 1 shows the experimental set-up and the hands of a subject with markers attached to the fingers. Marker positions are determined by image based motion analyzers, using a sampling rate of 100/s (with the system called PRIMAS, see below) or 50/s (with the system called PAM, see below).

PRIMAS is a real-time, precision, image-based motion analyzer that is able to determine marker positions in three dimensions (Furnée and Jobbágy, 1993). Its performance, similarly to the performance of commercially available marker-based motion analyzers, by far exceeds the requirements needed to record and evaluate the finger-tapping movement. Such analyzers, however, are too expensive and are not usually applied in routine clinical tests. A passive marker-based motion analyzer (PAM) has been assembled using a commercially available video camera (SONY TR8100E). The digital video (DV) output of the camera is connected to a PC via a standard IEEE1394 interface. The camera can be set so as to be sensitive in the infrared range. 18 infrared LEDs have been fitted around the lens and the

Table 1
Parkinsonians tested

Patient number	Age	Gender	Hoehn–Yahr stage	Handedness
P1	53	m	1–2	r
P2	69	m	2–3	r
P3	55	m	1	r
P4	76	m	1	r
P5	45	f	2	r
P6	69	f	1	r
P7 (newly diagnosed)	65	f	0–1	r
P8 (newly diagnosed)	65	m	0–1	r
P9 (same as P4)	77	m	1	r
P10	72	f	2	l
P11 (same as P2)	70	m	2–3	r
P12 (same as P8)	66	m	1	r
P13 (same as P10)	72	f	2	l
P14	65	m	1	r
P15 (same as P8)	67	m	1	r
P16 (same as P7)	67	f	1	r
P17 (same as P4)	78	m	1	r
P18 (same as P10)	73	f	2	l

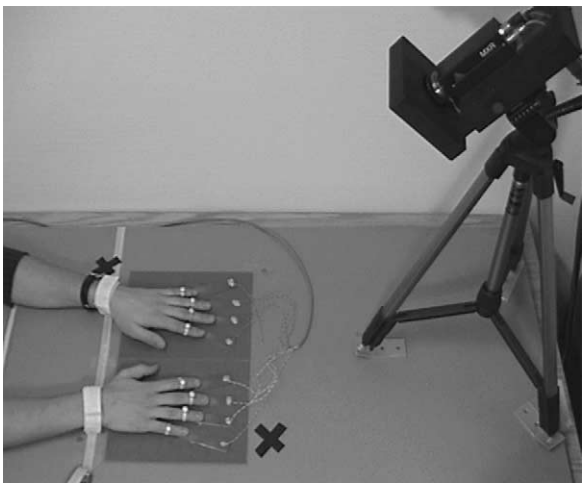

Fig. 1. Retro reflective markers attached to the fingers of a tested subject and the measurement set-up. Table with metal stripes and bands around the wrists assure the reproducible hand-camera arrangement.

necessary control circuitry has been developed. The infrared LEDs aid the separation of marker images from the rest of the image, and they increase the ambient light suppression. The 1-ms flashing of the LEDs is synchronized to the vertical synchronous pulse in the video signal of the camera, and ensures a sharp marker image. Fig. 2 shows two fields (odd and even) separately and together as one frame taken by PAM in the infrared range. The displacement of the markers between two fields (over a period of 20 ms) can be observed in the frame displaying both odd and even fields. Each field in the digital video is processed at a sampling rate of 50/s. Finger-tapping is characterised by the vertical coordinates of the marker positions, and can be evaluated from the images recorded with a two dimensional analyzer.

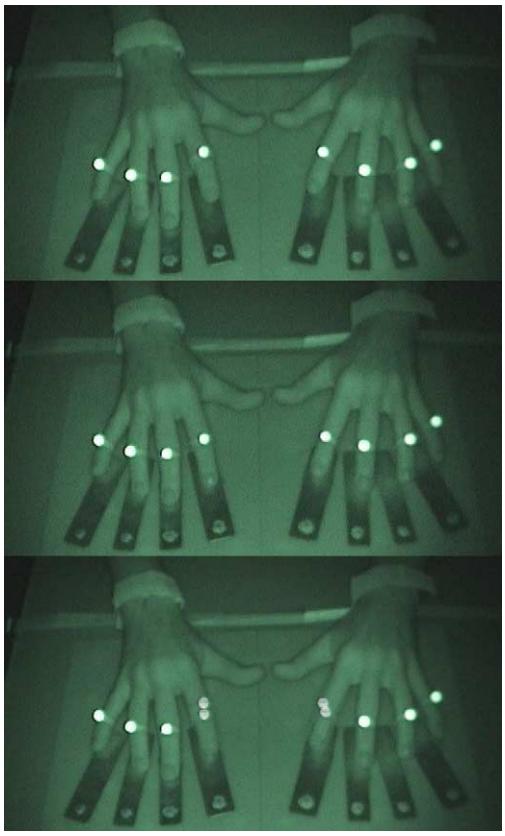

Fig. 2. The odd field (top); even field (middle) and the two fields displayed as one frame (bottom) recorded with PAM during finger-tapping test.

2.3. The necessary sampling rate

The sampling rate necessary for the evaluation of the finger-tapping movement was determined using PRIMAS. Marker position data were initially gathered with a sampling rate of 100/s. The database was reduced in two steps, each time eliminating every second data. Thus the database after the first reduction corresponds to a sampling rate of 50/s and after the second reduction to 25/s. In this way, three databases describing every tested finger-tapping movement were produced. Strong agreement has been found between parameter values computed based on the first (100/s) and the second (50/s) databases, but they were markedly different from those calculated using the third database (25/s). These results are in accordance with the frequency domain analysis of the time functions achieved with a sampling rate of 100/s, which shows that components above 22 Hz are negligible. This is clearly shown in Fig. 3, which depicts the Fourier transform of the movement of a marker attached to the little finger of a young healthy subject. Similar energy distribution over frequency was detected also for other healthy subjects, whereas Parkinsonian patients usually had energy distribution not higher than around 16 Hz.

2.4. The finger-tapping movement

The subjects are asked to put their hands on the table in the prone position, with fingers approximately 1 cm apart from each other, and 9-mm diameter markers are attached to the middle phalanxes of their fingers with the elbows on the table. They then lift their fingers (except thumbs) and then tap the table in the following order: little, ring, middle, and index finger. They are asked to perform this movement as fast

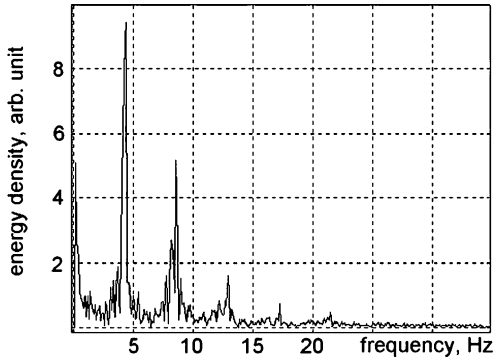

Fig. 3. Fourier transform of the movement of the little finger during tapping test (young healthy subject). Energy density is negligible above 22 Hz.

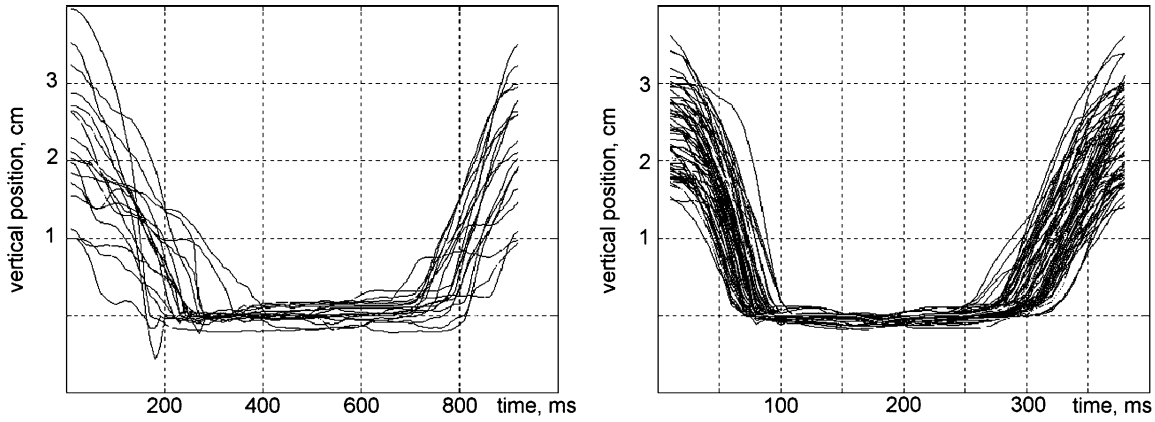

Fig. 4. Tapping periods of a Parkinsonian (left) and a healthy control subject (right).

as they can and to lift their fingers as high as they can. Both hands should complete the same movement, thus mimicking piano playing. Two adjacent phases of the movement can be seen in Fig. 2.

2.5. Feature extraction methods

The primary input data are the marker trajectories. Several feature extraction methods were compared to find the proper parameters characterizing the performance of tested persons during finger-tapping. The following features were determined: frequency spectrum, measure of periodicity, tapping speed expressed by amplitude × frequency of tapping. The frequency spectrum of the position–time function of a marker was determined by fast Fourier transform. The measure of periodicity of the quasi-periodic movement of a finger can be quantified by using the singular value decomposition (SVD) method (Kanjilal et al., 1997; Stokes et al., 1999). Unlike the Fourier analysis, the signal is broken down to all possible periodic functions, not only sinusoidal. For each finger the vertical co-ordinates of the sampled marker positions (with one sample) can be regarded as a vector, $\boldsymbol{y}$:

$$\boldsymbol{y} = \boldsymbol{y}(1)\ \boldsymbol{y}(2)\ \ldots\ \boldsymbol{y}(k)\ \ldots\ \boldsymbol{y}(\ell)$$

The local maximum values $\boldsymbol{y}$ (pi) mark the beginning of the ith period. Row vector $\boldsymbol{r}$ (i) is comprised of samples belonging to the ith period.

$$\begin{aligned}\boldsymbol{r}(1) &= [\boldsymbol{y}(\mathrm{p}1)\ \boldsymbol{y}(\mathrm{p}1+1)\ \ldots\ \boldsymbol{y}(\mathrm{p}2-1)]\\ \boldsymbol{r}(2) &= [\boldsymbol{y}(\mathrm{p}2)\ \boldsymbol{y}(\mathrm{p}2+1)\ \ldots\ \boldsymbol{y}(\mathrm{p}3-1)]\\ &\vdots\\ \boldsymbol{r}(m) &= [\boldsymbol{y}(\mathrm{p}m)\ \boldsymbol{y}(\mathrm{p}m+1)\ \ldots\ \boldsymbol{y}(\mathrm{p}m+c)]\end{aligned}$$

As a first step, the $\boldsymbol{y}$ vector must be segmented into periods. The periods can be aligned at the maximum vertical positions of the markers (see Fig. 4). The SVD method requires

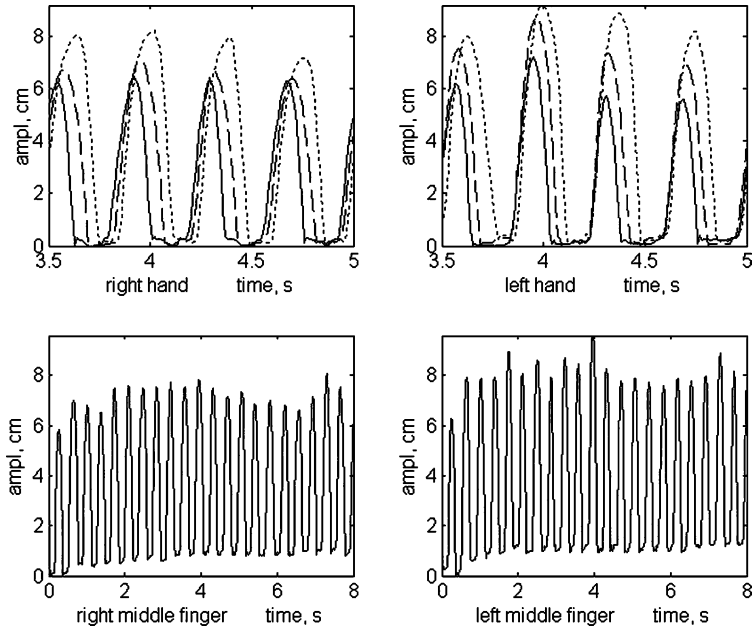

Fig. 5. Healthy young subject (CSP8). (Solid = ring; dashed = middle; dotted = index finger).

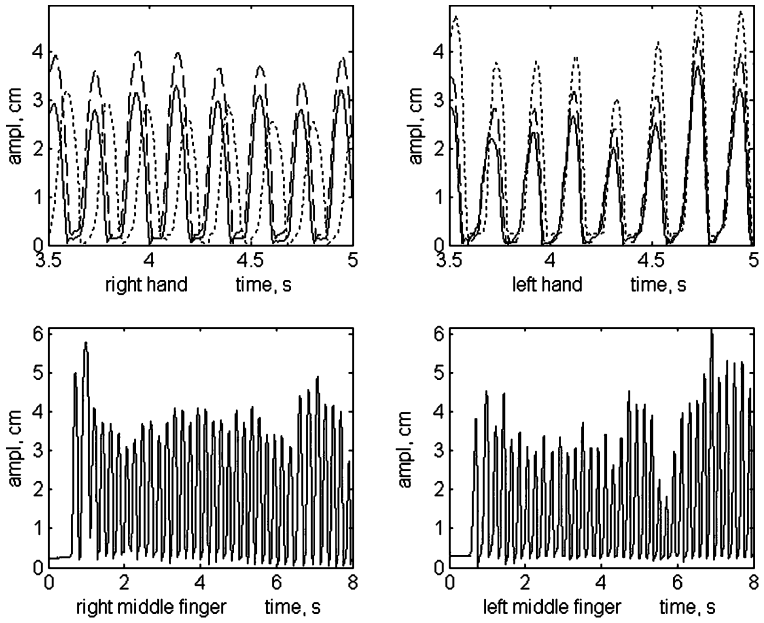

Fig. 6. Healthy senior subject (S04). (Solid = ring; dashed = middle; dotted = index finger).

that the lengths of $\boldsymbol{r}$ (i) vectors be the same. The equal length of all $\boldsymbol{r}$ (i) vectors is assured by resampling the data in each row. The median (denoted by n) of the lengths of the $\boldsymbol{r}$ (i) vectors will be the length of each resampled vector.

$$\text{length}(\boldsymbol{r}(i)) = \begin{cases} (i < m) : \text{p}j - \text{p}i, & j = i + 1 \\ (i = m) : c + 1 \end{cases}$$
$$n = \text{median}(\text{length}(r(i)))$$

Resampling is accomplished by linear interpolation. The first and last elements of the resampled row vectors are the same as in the original row vectors $\boldsymbol{yr}(i, 1) = \boldsymbol{y}(\text{p}i)$, $\boldsymbol{yr}(i, n) = \boldsymbol{y}(\text{p}(i + 1)-1)$ except for the last row vector, where $\boldsymbol{yr}(m, n) = \text{y}(\text{p}m + \text{c})$. Further elements of the resampled row vectors $\boldsymbol{yr}(i, j)$ are calculated by interpolation.The matrix thus created is:

$$X = \begin{bmatrix} yr(1,1)\, yr(1,2) \ldots yr(1,n) \\ yr(2,1)\, yr(2,2) \ldots yr(2,n) \\ \vdots \\ yr(m,1)\, yr(m,2) \ \ldots \ yr(m,n) \end{bmatrix}$$

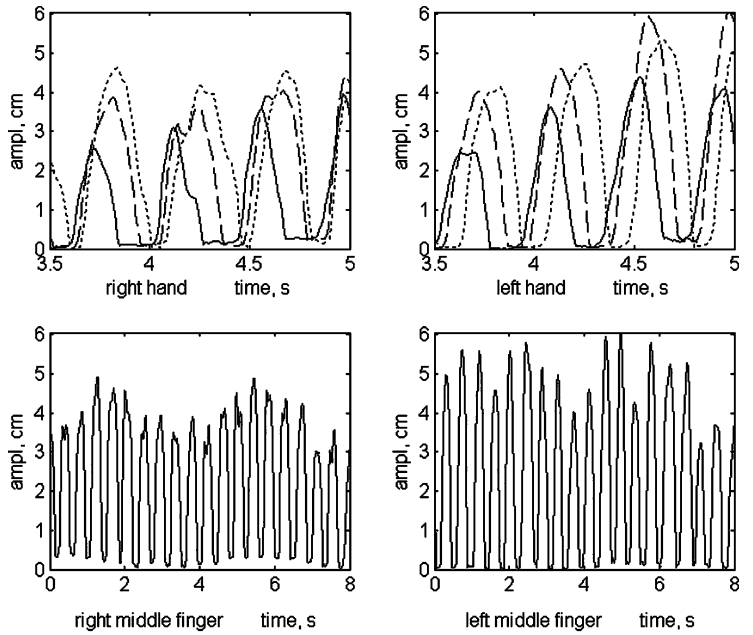

Fig. 7. Parkinsonian patient, newly diagnosed (P07). (Solid = ring; dashed = middle; dotted = index finger).

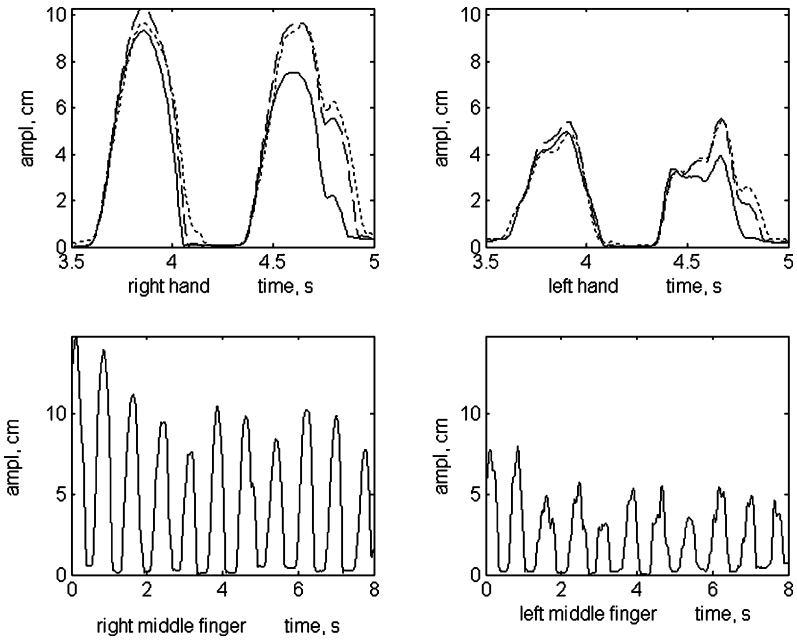

Fig. 8. Parkinsonian patient, newly diagnosed (P08). (Solid = ring; dashed = middle; dotted = index finger).

When the matrix is composed the SVD function of MATLAB® (The MathWorks Inc.) is used. This determines the matrices S, V and Σ so that $X = S\Sigma V^{T}$. A detailed description of the SVD method is given in Kanjilal and Palit (1994). Σ is a diagonal matrix, and its σ_i elements can be regarded as weighting factors of the basis functions that are needed to describe the $\boldsymbol{y}$ vector. The columns of V can be regarded as basis functions. The periodicity of movement (PM) is characterised by the ratio of the dominant basis function and all functions necessary to describe the complete record, i.e. all periods. This is calculated on the basis of the weighting factors (diagonals of Σ) σ_i.

$$\mathrm{PM} = \frac{\sigma_1^2}{\sum_{i=1}^{n}\sigma_i^2}$$

If all σ_i except σ_1 are zero then the movement is strictly periodic; it can be fully described with no more than one base vector. As a result, the parameter value PM = 1. In the case of a nearly periodic movement σ_1 is dominant but further

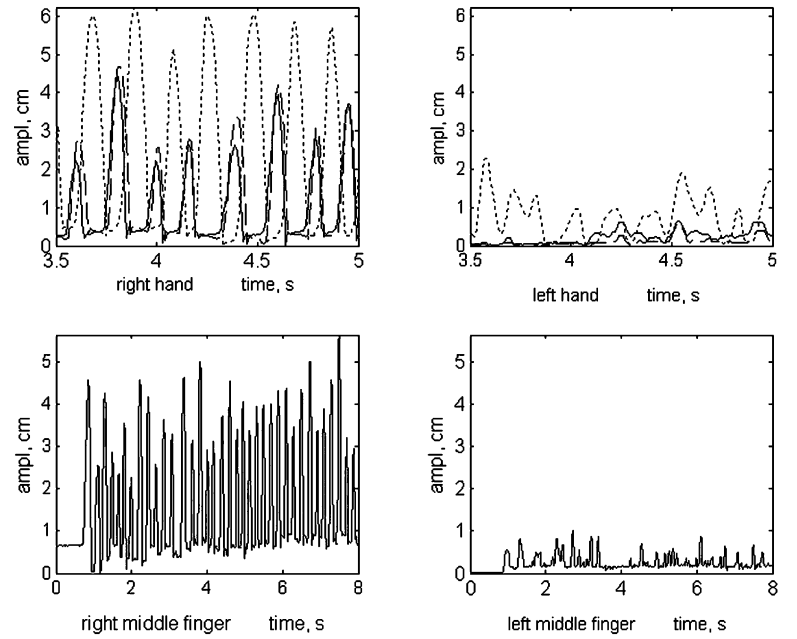

Fig. 9. Parkinsonian patient, Hoehn-Yahr stage 1 (P01). (Solid = ring; dashed = middle; dotted = index finger).

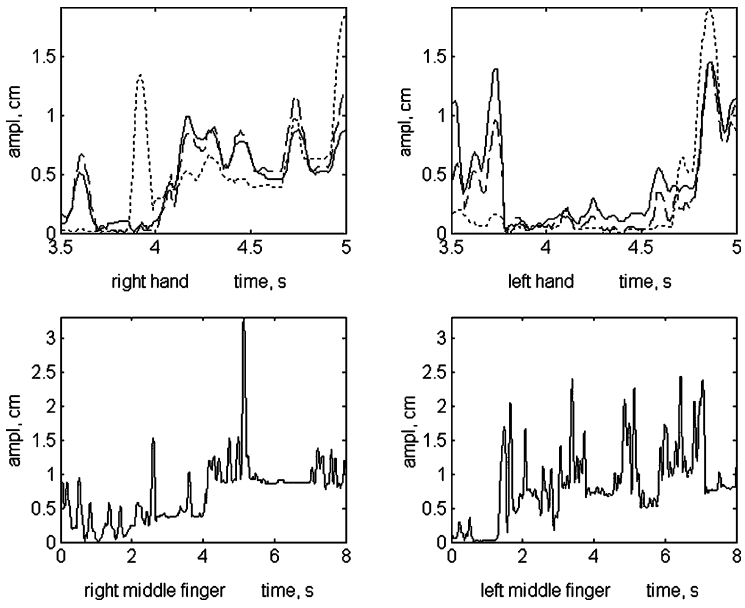

Fig. 10. Parkinsonian patient, Hoehn-Yahr stage 2 (P05). (Solid = ring; dashed = middle; dotted = index finger).

σ_i values are non-zero. The PM parameter value decreases as further vectors are needed to describe all periods of the complete movement.

Greater amplitude or greater frequency during finger-tapping means faster finger movement. This is considered as better performance. The movement can be executed faster with smaller amplitude. As a novel hypothesis, the amplitude × frequency of tapping is suggested to characterise the speed. This parameter is determined for each tapping cycle and then averaged over the whole test.

$$\text{amxfr} = \frac{\sum_{i=1}^{n}(A_i/T_i)}{n}$$

where, A_i is amplitude of the ith tapping cycle in centimetre, T_i is the time period of the ith tapping cycle in seconds, n is the number of tapping cycles during the whole test, amxfr is in centimetre/second.

2.6. Procedure

The actual states of 10 Parkinsonian patients were assessed based on different hand- and finger movements. Five Parkinsonians were also tested about a year after the first test, and three of them repeated the tests two years after the first test. The finger-tapping test was always completed by the patients. Seven of the patients repeated the finger-tapping

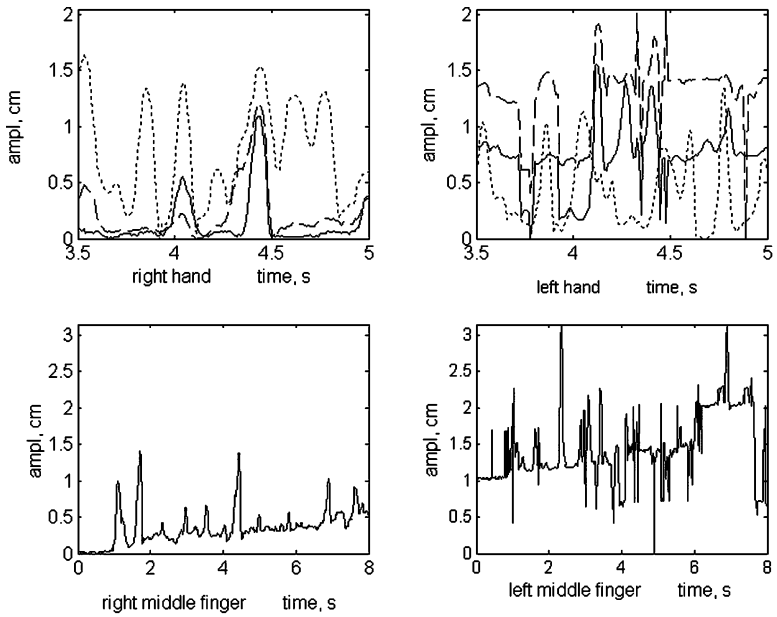

Fig. 11. Parkinsonian patient, Hoehn–Yahr stage 2–3 (P02). (Solid = ring; dashed = middle; dotted = index finger).

test after a short break, resulting in a total of 25 recordings of finger-tapping from Parkinsonians. At the beginning the finger-tapping test lasted for 8 s (21 tests of Parkinsonians, 25 tests of young and 17 tests of senior healthy subjects). The rest of the tests lasted for 30 s.

Different hand and finger movement of 21 young and 11 senior healthy subjects were assessed, resulting in 42 (25 + 17) recordings of finger-tapping. One senior and five young healthy subjects completed only the finger-tapping test a number of times within half a year. Two subjects completed the finger-tapping test 31 times, the other four subjects 7, 8, 14 and 15 times.

2.7. Quantification of the finger-tapping test

The finger-tapping movements were characterised by processing the position–time functions of the markers. The person gets a good score if the tapping speed is high (measured by amplitude × frequency) and the movement is close to periodic (measured by PM). Both tapping speed and periodicity of finger movement are taken into account in the proposed novel parameter, the finger-tapping test score (FTTS):

$$\mathrm{FTTS} = (\mathrm{PM} - 0.6) \times \mathrm{amxfr}.$$

The multiplication in the formula indicates that the periodicity of the movement can be maintained easier at a lower speed. The FTTS for a hand is calculated by averaging the FTTS values of the ring, middle and index fingers. PM for any of these fingers has been found to be between 0.84 and 0.99 for healthy subjects and 0.58 and 0.98 for Parkinsonians. For the same fingers amxfr has been 38–80 cm/s for healthy subjects and 4–80 cm/s for Parkinsonians. The proper relative weight for the two variables in the FTTS formula is set by subtracting 0.6 from PM. This means that FTTS is influenced equally by periodicity and speed of the movement. As PM is dimensionless, FTTS is given in centimetre/second.

The frequency spectrum of the position–time function of a marker was not characteristic for any tested person (Jobbágy et al., 1998).

3. Results

Figs. 5–11 show the time functions of the vertical co-ordinates of markers attached to fingers on both hands, for seven persons. In these figures, the upper panels show 1.5-s long sections of the movement of the ring, middle and index fingers, and the bottom panels 8-s long sections of the movement of the middle fingers (note that within one figure, the upper and lower panels have the same scales).

Fig. 12 shows the FTTS parameters of the healthy senior subjects (except JA who participated in the repeatability test), and Fig. 13 shows FTTS of the Parkinsonian patients. The mean value and the standard deviation of FTTS determined for young and senior healthy subjects and Parkinsonians in Hoehn–Yahr stage I are given in Table 3. Only S09 and S11 exhibit substantial differences between the two hands, with a difference of less than 1:2. The Parkinsonian patients are ordered according to their Hoehn–Yahr staging, and a horizontal bar connects the results of the same patient. P07 and P08 were first tested when they were diagnosed.

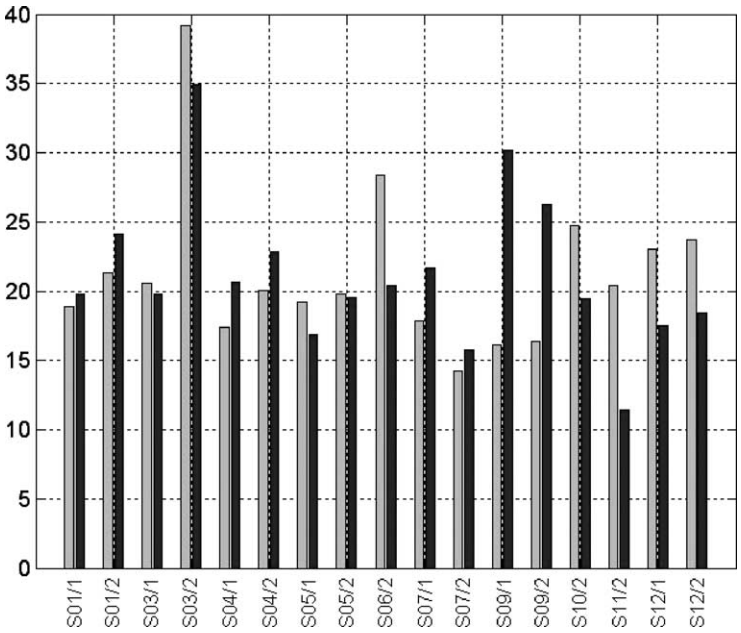

Fig. 12. FTTS scores of senior healthy subjects. Bright bars stand for the right hands and dark bars for the left.

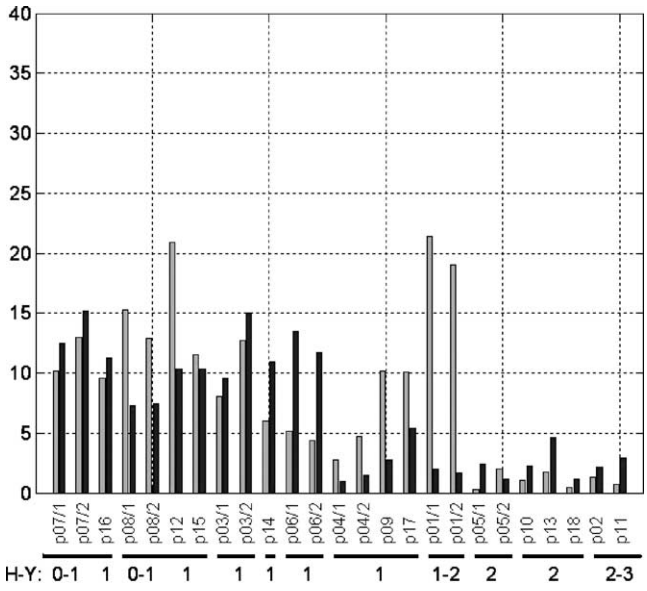

Fig. 13. FTTS scores of Parkinsonian patients. Bright bars stand for the right hands and dark bars for the left. Horizontal bars connect the recordings of the same patients. Hoehn–Yahr staging of patients is shown below the bars.

Table 4
Results of the measurement series of healthy subjects

Subject	Age	Sex	Experienced	Number of tests	Mean and S.D./mean of FTTS			
					Right hand (cm/s)		Left hand (cm/s)	
CSP	22	m	Y	15	20.2	0.05	22.9	0.06
FA	22	f	Y	14	19.7	0.06	25.7	0.08
RM	21	f	N	7	20.8	0.24	18.7	0.30
				(first 3)	26.0	0.08	24.3	0.03
				(last 4)	17.0	0.11	17.0	0.16
KRI	22	f	Y	8 (last 6)	13.9	0.21	10.0	0.24
					15.2	0.04	11.1	0.05
MP	23	m	N	31	21.4	0.26	17.6	0.27
JA	52	m	Y	31	36.2	0.08	37.4	0.06
10 Senior			N	17	18.6	0.27	21.2	0.26
16 Young			2/16	25	21.0	0.19	21.4	0.18

Table 3
Mean and S.D. of FTTS of Parkinsonians in Hoehn–Yahr stage 1 and of healthy subjects who did not participate in the repeatability test

FTTS	Right hand		Left hand	
	Mean (cm/s)	S.D. (cm/s)	Mean (cm/s)	S.D. (cm/s)
Young	19.8	4.2	20.1	5.8
Senior	26.4	8.8	26.8	9.1
Parkinsonians in H–Y 1	8.7	4.9	9.1	4.7

The FTTS of P07 is about the same as the FTTS of the worst performing senior healthy subject (S07, second test). The left hand of P08 is affected by the disease, and the related FTTS is much worse than the worst FTTS of senior healthy subjects. The FTTS of the right hand of the patient (P08, P12, P15 stand for the same person) varies, but it is never much worse than the average of healthy subjects. The FTTS of P03 is also quite close to the mean FTTS of senior healthy subjects. P14 and P06 performed in a similar way to P08 with the difference that their right hands were affected by the disease. P04 (the same as P09 and P17) gradually improved his performance, though the FTTS of his left hand remained much worse than that of his right hand. The FTTS of the right hand of P01 is as good as that of a healthy senior subject, while the FTTS of the left hand is worse by a factor of 1:8. Parkinsonians with Hoehn–Yahr staging 2 or 3 could attain only very small FTTS values.

3.1. Repeatability of the finger-tapping test

Fig. 14 shows the repeatability of the test for a young healthy subject (CSP). CSP is an experienced person (he has learnt to play the piano). His results were similar to the average amxfr but the standard deviation for this parameter was low: mean values 22.9 cm/s and 20.2 cm/s, standard deviations 1.0 cm/s and 1.4 cm/s. The periodicity of his movement was the best among all subjects: PM-0.6 was 0.384 and 0.377, standard deviations 0.0026 and 0.0033.

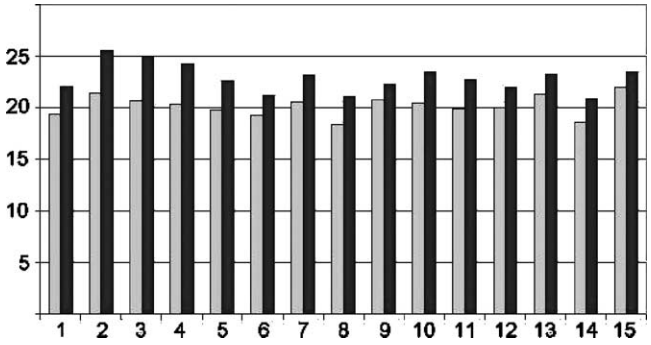

Fig. 14. FTTS scores of an experienced young healthy subject (CSP) taken during a 4-week period. Bright bars stand for the right hand and dark bars for the left.

The standard deviation/mean values of FTTS of the healthy control subjects who participated in the repeatability test are given in Table 4. Experienced persons exhibit better repeatability.

KRI increased her performance substantially up to the third test, probably as at the beginning she was excited by participating to the test. Omitting her first two tests, the standard deviation/mean value is as good as for other experienced subjects. RM was tested on two different days. The standard deviation of her performance on the same day was

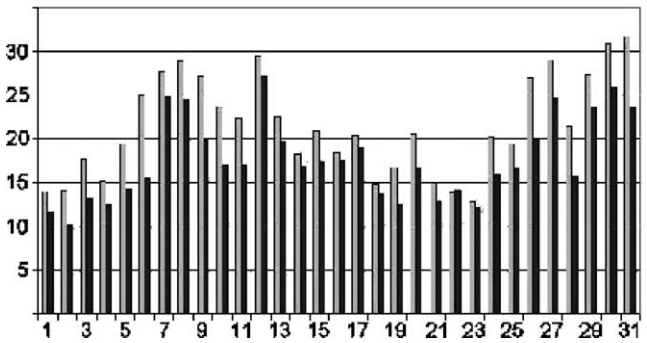

Fig. 15. FTTS scores of a young healthy subject (MP) during a 6-week period. Bright bars stand for the right hand and dark bars for the left.

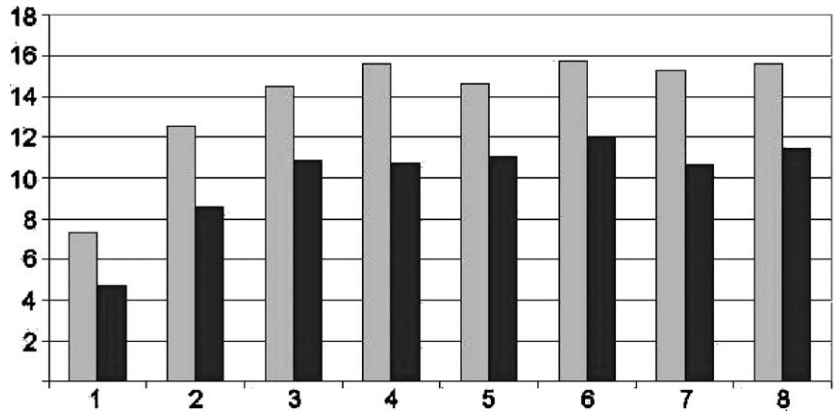

Fig. 16. The learning effect. FTTS scores of a young healthy subject (KRI) during a 2-week period. Bright bars stand for the right hand and dark bars for the left.

much smaller than the standard deviation of all her tests. Fig. 15 shows the FTTS values of a young healthy subject (MP) who exhibited the worst repeatability among healthy subjects. The repeatability of the measure of periodicity was much better for him than the repeatability of amxfr. PM-0.6 was 0.368 and 0.341 (standard deviations 0.0058 and 0.014). The amxfr values were 21.4 cm/s and 17.6 cm/s, standard deviations 5.7 cm/s and 4.7 cm/s.

3.2. The selectivity of the finger-tapping test

The FTTS for each Parkinsonian patient is smaller than the average for healthy subjects. Table 3 shows the results of healthy subjects and Parkinsonians in Hoehn–Yahr stage I. Jobbágy et al. (2000) give details of assessing Parkinsonian patients based on finger-tapping and two other hand- and finger movements.

3.3. The learning effect

Our results show that some persons—even healthy subjects—improve their performance substantially as they learn the movement and get accustomed to the test environment. This means that the first 2–3 recordings taken from a person may prove to be inaccurate for assessing his/her actual state. This is in agreement with the results of Wu et al. (1999), and suggests that at least two or three baseline tapping tests are needed to determine the baseline value of the tapping test. Fig. 16 shows an example for the learning effect. There is a marked increase in FTTS and from the third test on the FTTS values are quite stable.

4. Discussion

The human ability to process images is excellent as long as the images are static, and it is known that visual evaluation of a movement can give only a rough quantification if proper instrumentation is not used (Tosi, 1992). The time intervals between successive finger tapping on a table can be measured with simple contact sensors, and marker-based motion analysis makes it possible to observe details of a movement on a still image. The recorded trajectories also give information about the finger movement between contacts with the table, thus allowing a finer quantification of the movement. In this study we propose the use of a novel parameter, FTTS, to rate the finger-tapping movement. Both speed and periodicity of the movement influence FTTS, and this new score may help in routine assessment of the stage of the disease in Parkinsonian patients.

Among those healthy subjects who did not participate in the repeatability test, the senior group had greater FTTS mean values than the young group but the related standard deviations for the senior group was also greater (see Table 3). Parkinsonians achieved smaller FTTS than healthy subjects. In harmony with the unilateral symptoms, there are often substantial differences between the scores of the two hands of Parkinsonians.

The early diagnosis and assessment as well as staging of Parkinsonian patients is more reliable if further movement patterns (Rao et al., 2003) are also involved in the test. For a given patient, some movement patterns are affected more severely by the disease than others, and Jobbágy et al. (1998) have recommended personalisation of tests. As for the finger-tapping test, the score of one or more fingers can be more informative than the score of a hand.

To improve repeatability, both the movement patterns and the instructions given to the subject have to be presented clearly and in detail.

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