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Measurement and Evaluation of Finger Tapping Movements Using Magnetic Sensors

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***Abstract*— This paper proposes a quantitative measurement and evaluation method of finger tapping movements for diagnosis support and assessment of motor function. In this method, a magnetic sensor consisting of two coils is used to measure movement. The coil voltage induced by the electromagnetic induction law changes depending on the distance between the two coils; this enables estimation of the distance between two coil-bearing fingertips from the voltage measured by the nonlinear modeling relationships between the voltages and distances. Further, the finger movements measured are evaluated by computing ten indices such as the *finger tapping interval*, and radar charts of the evaluation indices and phase-plane trajectories of the finger movements are then displayed in real time on a monitor. Evaluation experiments were performed on finger movement in 16 Parkinson's disease patients and 32 normal elderly subjects, with the results showing that all evaluation indices differ significantly for each subject ($p < 0.05$).**

I. INTRODUCTION

Parkinson's disease (PD) is a progressive, incurable disease that affects approximately one in five hundred people (around 120,000 individuals) in the UK [1]. Assessment of its symptoms through blood tests or clinical imaging procedures such as computed tomography (CT) scanning cannot fully determine the severity of the disease. Evidence obtained from clinical semiology and the assessment of drug therapy efficacy therefore depend on the doctor's inquiries into the patient's status, or on complaints from patients themselves.

To determine neurological disorders such as PD or spinocerebellar degeneration, various assessment methods have been used including thenen open-close movement, pronosupination and finger tapping movement [2]. Since Holmes [3] proved that the rhythm of finger tapping movements acts as an efficient index for cerebellar function testing, such movements have been widely applied in clinical environments. Generally, the Unified Parkinson's Disease Rating Scale (UPDRS) [2] is used to assess the severity of PD in patients. However, this method is semiquantitative, and has drawbacks including the vagueness of the basis of evaluation for determining the course of the disease [4]. It would therefore be practical if clinical semiology and the efficacy of drug therapy could be evaluated easily and quantitatively from finger tapping movements.

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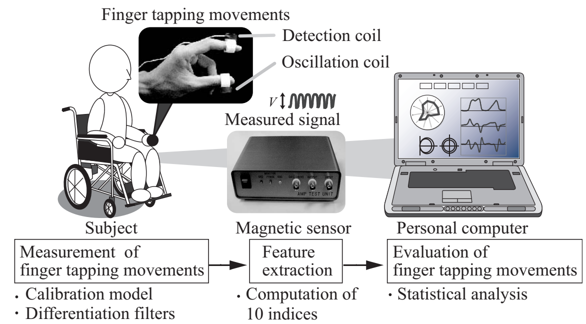


Fig. 1. Overview of the proposed system

The quantification of finger tapping movements has already been extensively investigated through techniques such as evaluating tapping rhythms using electrocardiographic apparatus [5] and examining the velocity and amplitude of movements based on images measured by infrared camera [6], [7]. These camera systems can capture the 3D motion of fingers, but require large and expensive equipments. Further, a compact, lightweight acceleration sensor [8], [9] and magnetic sensor [10] have been utilized for movement analysis in recent years. As for the evaluation of finger tapping movements, however, only the basic analyses have been performed such as verification of the feature quantities of PD patients, which have never been used for the routine assessment of PD in clinical environments.

The purpose of this study is to realize a PD assessment system for use in general clinical environments, and to this end we propose a novel measurement and evaluation method for finger tapping movements. This system measures finger movements with high accuracy using magnetic sensors [10], and includes a novel nonlinear calibration model for the sensors. Further, ten evaluation indices consisting of feature quantities extracted on the basis of medical knowledge (such as the maximum amplitude of the measured finger taps) are computed, and radar charts of the evaluation indices and phase-plane trajectories of the measured movements are then displayed in real time for doctors on a monitor. The user can therefore intuitively understand the features of finger tapping movements and compare them with previous measurements or other data.

II. MEASUREMENT AND EVALUATION SYSTEM

The measurement and evaluation system of finger tapping movements is shown in Fig. 1. It consists of a magnetic sensor and a personal computer (PC). The user conducts finger tapping movements with two magnetic sensor coils attached to the distal parts, and the magnetic sensor then outputs voltages according to the distance between the two coils. The voltages measured are converted into values representing the distance between the two fingertips (the *fingertip distance*) based on a nonlinear calibration model in the PC. Further, the features of the movements measured are computed for evaluation of the finger taps. The details of each process are explained in the subsections below.

A. Measurement of finger tapping movements

In this paper, the magnetic sensor developed by Kandori *et al.* [10] is utilized to measure finger tapping movements. The sensor can output a voltage corresponding to changes in distance between the detection coil and the oscillation coil by means of electromagnetic induction. First, the two coils are attached to the distal parts of the user's fingers, and finger tapping movements are measured. The fingertip distances are then obtained from the output voltage by a calibration model expressed as

$$d(t) = \alpha\tilde{V}(t) - \varepsilon \quad (1)$$

$$\tilde{V}(t) = V^{-\frac{1}{3}}(t) \quad (2)$$

where $d(t)$ denotes the fingertip distance, $V(t)$ is the measured voltage of the sensors at a given time t, and α and ε are constants computed from the calibration. In the calibration process, α and ε are estimated using the linear least-square method for n values measured output voltages and the fingertip distances of each subject. The calibration process can reduce the influence of the slope of the coils and modeling errors [11]. Further, the velocity $v(t)$ and acceleration $a(t)$ can be calculated from the fingertip distance $d(t)$ using differentiation filters.

B. Feature extraction

The evaluation indices of finger tapping movements are calculated for quantitative evaluation at the feature extraction stage. This paper defines ten indices based on previous observations [8], [9] as follows:

1) *Total tapping distance*
2) *Average maximum amplitude of finger taps*
3) *Coefficient of variation (CV) of maximum amplitude*
4) *Average finger tapping interval*
5) *CV of finger tapping interval*
6) *Average maximum opening velocity*
7) *CV of maximum opening velocity*
8) *Average maximum closing velocity*
9) *CV of maximum closing velocity*
10) *Average zero-crossing occurrences of acceleration*

First, the integration of the absolute value of velocity $v(t)$ through the measurement time is signified as the total tapping distance (Index 1). The number of fingertip contacts is also determined from $d(t)$, $v(t)$ and $a(t)$ for the extraction of a finger tap, and the distance d_j^{min}, which satisfies $v(t) = 0$ and $a(t) > 0$, is calculated from $d(t)$. The instant when the distance d_j^{min} decreases to below the threshold $M^{th}(\geq \zeta)$ defined by Eq. 3 is defined as the contact time T_i ($i = 1, 2, \ldots, I$, I is the number of contacts between fingertips).

$$M^{th} = \eta(\frac{1}{K}\sum_{k=1}^{K} d_k^{max} - \frac{1}{J}\sum_{j=1}^{J} d_j^{min}) \quad (3)$$

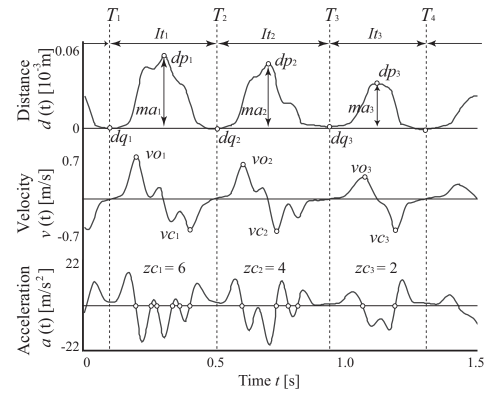


Fig. 2. Examples of the signals measured

Here, ζ and η are constants, d_k^{max} denotes the distance that satisfies $v(t) = 0$ and $a(t) < 0$, K is the number of d_k^{max}, and J is the number of d_j^{min}.

As feature quantities of the i^{th} tapping, the maximum and minimum amplitude points (dp_i, dq_i) between the interval $[T_i, T_{i+1}]$ are calculated from the measured fingertip distance $d(t)$, and the average (Index 2) and CV (Index 3) of maximum amplitudes $ma_i = dp_i - dq_i$ are computed. Further, the finger tapping interval It_i, which is the time interval between two consecutive contacts, is applied as $It_i = T_{i+1} - T_i$, and the positive and negative maximum velocity points are defined as the maximum opening velocity vo_i and the maximum closing velocity vc_i respectively. The averages and CVs of the finger tapping interval, maximum opening velocity and maximum closing velocity are then computed from all the values of It_i, vo_i, and vc_i (Indices 4–9) respectively.

In addition, zc_i, which denotes the number of zero crossings of the acceleration waveform $a(t)$, is calculated from each interval between T_i and $T_i + 1$, and the zero-crossing occurrences of acceleration zc_i are defined as the evaluation value of multimodal movements (Index 9). Here, the number of zero crossings zc_i increases in accordance with the number of extrema of $v(t)$ in a tap movement. As examples, $zc_3 = 2$ implies a smooth tap, while $zc_1 = 6$ or $zc_2 = 4$ would represent a jerky tap (see Fig. 2).

C. Evaluation of finger tapping movements

The calculated evaluation indices of the subject are normalized based on the indices of normal subjects to enable comparison of the difference in movements. Here, it was observed from the preliminary experimental results that three evaluation indices of PD patients (i.e. average maximum amplitude, maximum opening velocity and maximum closing velocity) were smaller than those of normal elderly subjects. These indices were used to calculate the inverse number for every single tap, and the total tapping distance was converted to its inverse number. Hence, all the indices of PD patients are greater than those of normal elderly subjects.

In this paper, the standard normally distributed variables x_j are converted to the mean and standard deviations of the tapping data from those of the normal subjects using Eq. 4.

$$x_j = (z_j - \mu_j)/\sigma_j \quad (4)$$

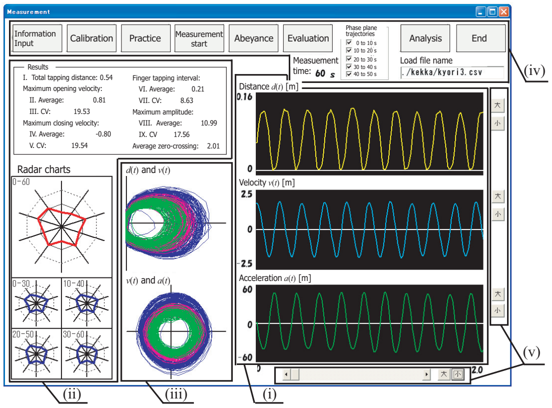


Fig. 3. Example of graphic display

Here, j corresponds to the index number, z_j is the computed value in each index, and μ_j and σ_j describe the average and standard deviation of each index in the group of normal elderly subjects respectively. $j = 1$ represents the total tapping distance, $j = 2, \ldots, 9$ signify the average and CV of maximum amplitude, finger tapping interval, maximum opening velocity and maximum closing velocity, and $j = 10$ denotes the average zero-crossing occurrences of acceleration. Each index for the normal elderly subjects follows a normal distribution as the average becomes 0 and the standard deviation becomes 1.

D. Graphical output

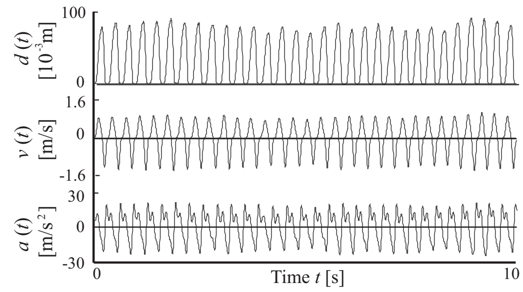
The measured signals, computed feature quantity and indices are displayed for doctors on a graphic display. An example of the operation of the proposed system is shown in Fig. 3. During operation, the monitor displays the following information: (i) the measured fingertip distance $d(t)$, velocity $v(t)$ and acceleration $a(t)$; (ii) computed indices and radar charts calculated for all measurement time and at prespecified time intervals; (iii) phase-plane trajectories of $d(t)$ and $v(t)$, and $v(t)$ and $a(t)$ on a real-time basis (the phase-plane trajectories can visually describe the dynamics of motion); (iv) operation buttons; and (v) a scrollbar to allow the waveform display time and the scale of the figure to be changed. Users can also input information and observations and use them for electronic medical charts and databases, which enables comparison with previous measurement data.

III. Evaluation Experiments of Finger Tapping Movements

We conducted evaluation experiments to identify the effectiveness of the proposed method for analysis of finger tapping movement.

A. Experimental conditions

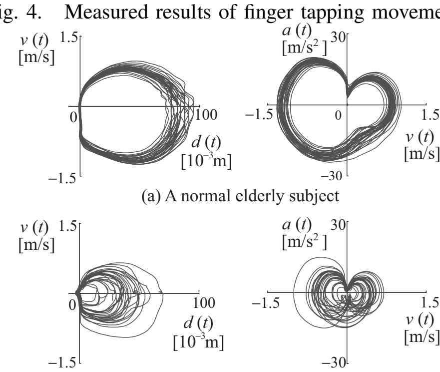
The subjects were 16 patients with PD (average age: 71.2 ± 6.4, male: 5, female: 11) and 32 normal elderly subjects (average age: 68.2 ± 5.0, male: 16, female: 16). The subjects were directed to assume a sitting posture at rest. The coils were attached to the distal parts of the thumb and index finger, and the magnetic sensor was calibrated using three calibration values of 20, 30 and 90 mm. After a brief finger tapping movement trial using both the left and right hands, the movement of each hand was measured for 60 s in compliance with instructions to move the fingers as far apart and as quickly as possible. The subjects were isolated from the electrical supply of the PC. The severities of PD in the patients were evaluated by a neuro-physician based on the finger tap test of UPDRS [2]. The investigation was approved by the local Ethics Committee, and written informed consent was obtained from all subjects. The calculated indices were standardized on the basis of values obtained from the normal elderly subjects. The parameters of analysis were $\eta = 0.1$ and $\zeta = 5$ mm, and the sampling frequency was 100 Hz.



(a) A normal elderly subject

(b) A patient with Parkinson's disease (UPDRS-FT 2)

Fig. 4. Measured results of finger tapping movements



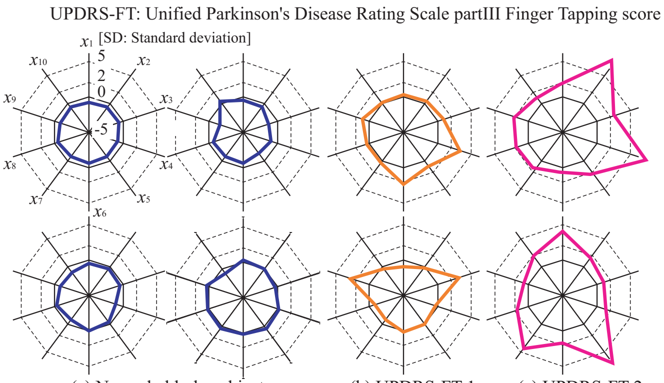
(a) A normal elderly subject

(b) A patient with Parkinson's disease (UPDRS-FT 2)

Fig. 5. Phase-plane trajectories of finger tapping movements

B. Results

Examples of the finger tapping movements and phase-plane trajectories of a normal elderly subject (a) and a PD patient (UPDRS-FT 2: UPDRS part III Finger Tapping score 2) (b) are shown in Figs. 4 and 5 respectively. Figure 4 plots the measured fingertip distance $d(t)$, velocity $v(t)$ and acceleration $a(t)$ waveforms. These figures show the results of the measured data during the period from 0 to 10 s. Further, a radar chart representation of the results of the indices is shown in Fig. 6; (a) to (c) illustrate the charts



(a) Normal elderly subjects (b) UPDRS-FT 1 (c) UPDRS-FT 2

Fig. 6. Examples of radar chart representation of the results of the evaluated indices

TABLE I

T-TEST RESULTS OF THE EVALUATION INDICES

Evaluation indices	Significance probability p			
	Normal elderly and PD	UPDRS-FT1 and -FT2	UPDRS-FT1 and -FT3	UPDRS-FT2 and -FT3
x_1	2.552×10^{-4} **	3.084×10^{-2} *	1.024×10^{-2} *	1.128×10^{-1}
x_2	9.345×10^{-7} **	2.751×10^{-1}	8.976×10^{-2}	1.062×10^{-1}
x_3	1.701×10^{-5} **	4.292×10^{-5}**	2.569×10^{-3}**	2.463×10^{-1}
x_4	3.694×10^{-3} *	4.916×10^{-1}*	2.869×10^{-1}	5.172×10^{-1}
x_5	1.265×10^{-2} *	2.126×10^{-1}**	4.332×10^{-2}*	8.354×10^{-2}
x_6	1.888×10^{-10}**	1.313×10^{-1}	3.218×10^{-2} *	5.820×10^{-2}
x_7	7.564×10^{-8} **	1.107×10^{-1}	2.289×10^{-2} *	8.890×10^{-2}
x_8	1.302×10^{-11}**	1.018×10^{-1}	4.477×10^{-2} *	7.164×10^{-2}
x_9	1.943×10^{-6} **	1.988×10^{-4} **	7.016×10^{-5} **	4.491×10^{-2} *
x_{10}	1.268×10^{-2} *	1.344×10^{-1}	6.900×10^{-2}	4.695×10^{-1}

x_1: Total tapping distance
x_2: Average maximum amplitude
x_3: CV of the maximum amplitude
x_4: Average finger tapping interval
x_5: CV of finger tapping interval
x_6: Average maximum opening velocity
x_7: CV of the maximum opening velocity
x_8: Average maximum closing velocity
x_9: CV of the maximum closing velocity
x_{10}: Average zero-crossing occurrences of acceleration

CV: Coefficient of variation, **: Significance level 1.0%, *: 5.0%

of normal elderly subjects, PD patients with UPDRS-FT 1 and those with UPDRS-FT 2 respectively. The solid lines describe the average number of normal elderly subjects, and the dotted lines show double and quintuple the standard deviation (2SD, 5SD) in Fig. 6. Further, in order to verify whether each index can evaluate Parkinsonian symptoms, the indices of PD patients and normal elderly subjects were compared using a heteroscedastic t-test. Table I shows the test results of each evaluation index.

C. Discussion

The evaluation experiments demonstrated that the movement waveforms of PD patients and normal elderly subjects have different tapping rhythms and scales, in which PD patients show larger variation in tapping rhythm and smaller scale than normal elderly subjects (Figs. 4 and 5). Further, by plotting radar charts of the indices of movements computed and standardized on the basic values obtained from normal elderly subjects, we identified that data from normal elderly subjects lie near the average, while those in PD patients' charts become larger according to the severity of their conditions. These results lead us to the conclusion that radar charts can comprehensibly present evaluation results and features of movement. Moreover, comparison of each index of PD patients and normal elderly subjects using a t-test shows that all indices differ significantly at the 1% level (x_1 to x_4, and x_6 to x_9) or the 5% level (x_4, x_5, x_{10}), and these results denote the same tendency mentioned in [8] and [9]. In the case of evaluating the severity of PD, however, the indices differing significantly at the 1% level between UPDRS-FT 1 and -FT 2, -FT 1 and -FT 3, and -FT 2 and -FT 3 are only three (x_3, x_5, x_9), two (x_3, x_9) and zero, respectively. Because the number of PD experimental subjects (16) was small, it is necessary to investigate and improve the indices for accurate evaluation of the severity of PD with an increased number of subjects.

IV. CONCLUSION

A movement measurement and evaluation system for quantitative analysis of finger movements is proposed in this paper. The system involves the computation of ten evaluation indices measured from finger movements using magnetic sensors. Further, the average and coefficient of variance (CV) of the tapping interval (x_4, x_5) and the average zero-crossing occurrences of acceleration (x_{10}) in normal elderly subjects and those of Parkinson's disease patients differ significantly at the 1% level, and the other indices differ significantly at the 5% level. From these results, we conclude that the proposed indices and system are effective for the quantitative evaluation of finger movements. Our future research will involve improving the evaluation indices in order to enable diagnosis of the severity of the disease, as well as investigating the effects of aging with an increased number of subjects.

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