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ORIGINAL CONTRIBUTION

Quantification of bradykinesia during clinical finger taps using a gyrosensor in patients with Parkinson's disease

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Abstract This study aims to develop a quantitative measure of bradykinesia which can be conveniently used during clinical finger taps test in patients with Parkinson's disease. A miniature, light-weight gyrosensor free from gravitational artifact was used for measurement of finger taps in order to impose minimal constraint on patients. Forty Parkinson's disease patients and 14 age-matched control subjects participated in the experiments. Subjects' finger taps in both right and left hands were scored by two independent neurologists according to the unified Parkinson's disease rating scale and were also measured by a gyrosensor. Four performance indices were derived from the gyrosensor signal of the index finger. All indices showed significant differences between control and patients ($P < 0.001$) and also significant correlations with the clinical finger taps score ($r = -0.73$ to -0.80, $P < 0.001$). ANOVA showed significant differences in all indices among different finger taps scores ($P < 0.001$), and post hoc tests showed significant differences in indices between most pairs of non-neighboring and part of neighboring pairs of finger taps scores ($P < 0.01$). The results suggest that indices from a gyrosensor can be used as quantitative measures of bradykinesia during the finger taps test.

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1 Introduction

Movement disorders such as bradykinesia, tremor, rigidity, and postural instability are regarded as the cardinal clinical features of Parkinson's disease (PD) [14]. Abnormalities of fine motor control (i.e., finger taps) are often among the first signs of motor impairment in patients with PD [15]. Therefore, bradykinesia and disturbances of rhythm formation that occur in PD are usually assessed through the finger taps test [9, 18]. However, finger tapping has been suggested as one of the most difficult items to assess [5].

Part III of the unified Parkinson's disease rating scale (UPDRS), the motor disability score, is the most widely used clinical rating scale for the assessment of movement disorders in PD patients. However, it relies on a physician's subjective scoring based on his/her clinical experience [12] and has limited resolution for detection of small changes in disease progression in very early stage PD [11]. Though a modified scale called MDS-UPDRS has been suggested as having better internal consistency [6], it is not yet widely used, and still depends greatly on the subjective decision and experience of each rater. Therefore, more objective and quantitative methods for assessment of bradykinesia during the finger taps test would be of considerable help in the diagnosis of PD and evaluation of medication efficacy.

Studies have been conducted for quantification of fine motor bradykinesia using tasks that differ from those of the clinically used finger taps test. They include alternating finger tapping task on two computer keyboard keys [7], alternating finger down-stroke on a musical instrument

digital interface (MIDI) keyboard [15], piano-playing-like finger tapping movement measured by precision image-based motion analyzer [8], and step tracking tasks using a joystick or a steering wheel [2]. However, correlations of suggested measures with clinical examination scores were relatively low (less than 0.63) and these systems were not employed either at the outpatient clinic or at the bedside [18], probably because use of the instruments was inconvenient and the tasks were not friendly to clinicians. Therefore, quantification of clinical finger taps, the standard clinical test, would greatly enhance the reliability of diagnosis in PD.

Analysis of clinical finger taps has been performed with a potentiometer [13], an optoelectronic motion capture system [1], an accelerometer [18], and a magnetic sensor system [9]. The potentiometer method required attachment of index finger and thumb to metal bars [13], which constrains natural finger tapping movement and limits its convenience and practicality. The accelerometer method also required constrained movement of fingers parallel to the desk surface in order to avoid gravitational artifact [18]. Methods other than potentiometer [1, 9, 18] analyzed linear amplitude, velocity, and acceleration of the finger tips, even though actual finger movement is rotational in nature and clinical assessment is based on its visual inspection. Moreover, in these studies, no statistical comparison with clinical score was performed [1], no statistical difference of extracted features among clinical score existed [9], and correlation with clinical finger taps score was relatively low ($r = -0.59$) [18].

A gyrosensor (which can be attached on a single finger segment) measures angular movement in terms of angular velocity and the sensor signal is free from gravitational artifact, so that it is expected to resolve all limitations of the above systems. The gyrosensor was shown to be useful for assessment of bradykinesia in forearm movement (alternating movement of hands) [10, 11]. However, there has been no study using the gyrosensor for assessment of bradykinesia during finger taps. Therefore, in this study, a gyrosensor system which can be used for measurement of finger taps was developed. Several performance indices were derived from the sensor signal, and their validity as quantitative measures of bradykinesia during clinically used finger taps test was evaluated through comparison with UPDRS finger taps score.

2 Methods

2.1 Measurement system

Figure 1 shows the structure of the developed system. A miniature and light-weight gyrosensor (6 × 10 × 25 mm, 0.26 g, CG-L53, NEC/Tokin, Japan) inserted in an elastic band (1.9 g including sensor) was attached on the top of the index finger with the sensing axis aligned to the finger tapping movement (flexion and extension). The thumb was excluded from measurement because angular velocity of the thumb was small and the rotation axis of thumb movement during finger taps did not match the joint axis of thumb flexion/extension, so that proper and consistent positioning of the sensor was difficult. Analog signal from the gyrosensor was amplified and sampled at 250 Hz by a microprocessor (Atmega8535) and transmitted to the PC through a serial port. This angular velocity signal was recorded by self-developed software using LabVIEW (National Instruments, USA) and analyzed using Matlab (The Mathworks Inc., USA).

2.2 Subjects and experiments

Forty patients with PD (20 men and 20 women, mean age 65.7 ± 11.1 years, HY stage: 2.3 ± 0.5, disease duration: 4.2 ± 2.9 years) and 14 age-matched control subjects (3

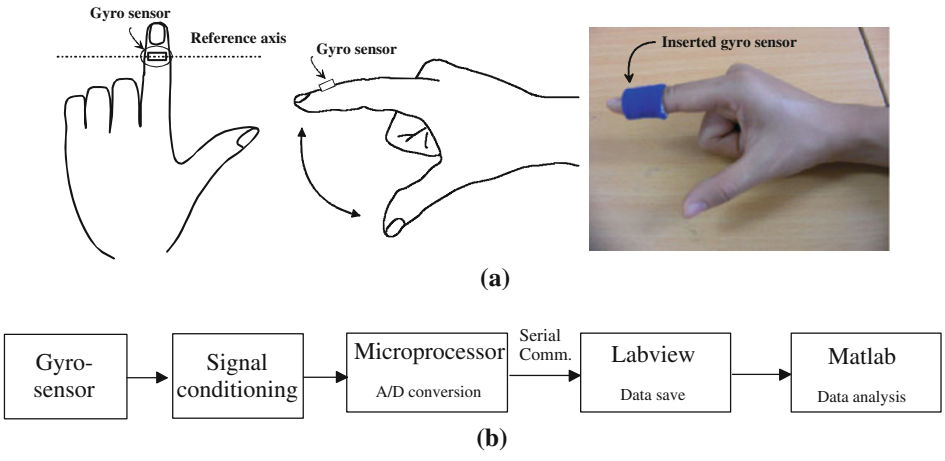

Fig. 1 **a** Sensor attachment and **b** schematic of the developed system

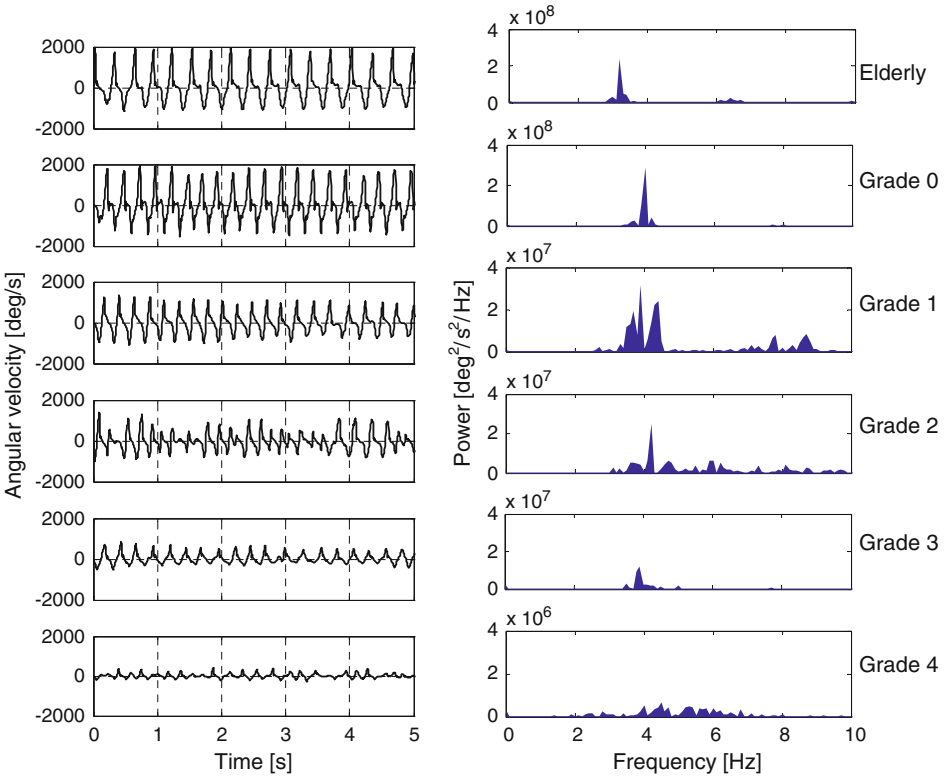

Fig. 2 Typical raw signals from gyrosensors and their power spectrums in patients with different finger taps scores as well as in healthy elderly subjects. Raw data for 5 s are shown, whereas 10 s of data were used in the analysis

men and 11 women, 65.0 ± 3.9 years) participated in this study. Patients were recruited according to Clinical Diagnostic Criteria described by the United Kingdom Parkinson's Disease Society Brain Bank. All subjects gave informed consent, and ethics committee approval was obtained for this study.

Subjects were instructed to tap their fingers in rapid succession with as large amplitude as possible, as described in the FT category of UPDRS [4]. After 5 s of practice and enough rest, the main test was performed for 10 s, which is the typical test time for finger taps in the clinic. As performance of multiple tests requires significant rest time for recovery from fatigue, thereby reducing the clinical usefulness, the main test was performed only once. During the main test, the gyrosensor signals were recorded and the FT movement itself was recorded by a digital video-recorder. Both left and right hands were tested. After the experiment, two independent neurologists rated FT score from investigation of the video files.

2.3 Analysis and statistics

A 4th-order zero-phase digital bandpass filter (1–50 Hz) was used to eliminate baseline drift and noise in the gyrosensor signal. The frequency range of the bandpass filter was determined from inspection of the power spectrum of the gyrosensor signal, i.e., the main component in the power spectrum was in 2–10 Hz and the peak frequency was in 3–6 Hz (Fig. 2), and there were no subjects with a main component lower than 1 Hz.

As evaluation of bradykinesia free from tremor was the purpose of the finger taps test, involuntary finger movement by tremor must also be eliminated from the signal. The frequency of the tremor is known to reside approximately 4–8 Hz [17]. However, some patients' voluntary movement, which was evident from video analysis by neurologists, showed peak amplitude in this frequency range with far greater amplitude than that of the tremor signal. This suggested that a lowpass filtering common to all subjects' signals would erroneously remove the voluntary movement in some cases. Therefore, we discriminated tremor from voluntary movement by inspection of the frequency spectrum; specifically, a signal in this frequency range with a peak amplitude lower than the manually set threshold (63 deg/s/Hz) was regarded as the tremor, so that an additional 4th-order lowpass filter ($f_c = 5$ Hz) was applied. In the process of threshold determination, existence of tremor was first decided by clinicians; the threshold was then set as the median value of maximum amplitude of tremor (verified from video) and minimum amplitude of voluntary movement on the amplitude spectrum.

Four performance indices (PIs) were derived from the sensor signal of 10 s. Two of them were time-domain

variables, i.e., root-mean-squared (RMS) angular velocity and RMS angular displacement. Each was expected to represent slowing of finger tapping motion and reduction in amplitude due to bradykinesia, respectively [16], which can be observed in the velocity and angle trajectories of Figs. 2 and 3. Angle was derived from the numerical integration of the angular velocity. The other two were frequency-domain variables, i.e., peak power and total power (the integrated area of the power spectrum) in the power spectrum of angular velocity. Each of them was expected to represent the intensity of the main movement component of finger tapping (repetitive flexion and extension) and the total intensity of movement, respectively. It is clear in Fig. 2 that peak power and total power of angular velocity decreased with bradykinesia score.

Each PI was tested against the standard measure. First of all, the inter-rater reliability of standard measure (FT score) was tested by Cronbach's alpha for consistency and also by intraclass correlation (ICC) for absolute agreement. The ability of each PI to represent or reflect the clinical rating was then evaluated in two ways. The first was the consistency of the relationship between a PI and clinical FT scores evaluated by Spearman's correlation. The second was the ability of a PI to differentiate patients from control subjects and to differentiate different FT scores. The former was evaluated by independent *t*-test of the difference in PI between control and patients (data scored as 0 by both raters were excluded from the patients group). The latter was evaluated by ANOVA and post hoc (Tukey) test of the difference in PI among different FT scores. In view of multiple comparisons, the level of significance was adjusted and defined as $P < 0.01$ [3]. All statistical analyses were performed using SPSS ver.16 (SPSS Inc., USA).

3 Results

Figure 4 shows the relations between PIs and FT score of each rater. All PIs show monotonic decrease with FT scores of both raters. Regarding the inter-rater reliability of the FT score, Cronbach's alpha was 0.85 and ICC coefficient was 0.74. Quantitative PI values of two raters differed significantly in FT score 0 where standard deviations were the greatest.

Table 1 shows the results of statistical analysis. Regarding the consistency of the relationship between PI and FT score, the correlation between PI and mean FT score of two raters was in the range -0.73 to -0.78 and the correlation between PI and FT score of each rater was in the range of -0.66 to -0.75 ($P < 0.001$). In both cases, the correlation coefficients of RMS velocity, peak power, and total power were comparable and better than that of RMS angle. Regarding the ability of PIs to differentiate patients from control, all PIs in patients were significantly lower than in the control ($P < 0.001$). Regarding the ability of PIs to discriminate different FT scores, ANOVA showed

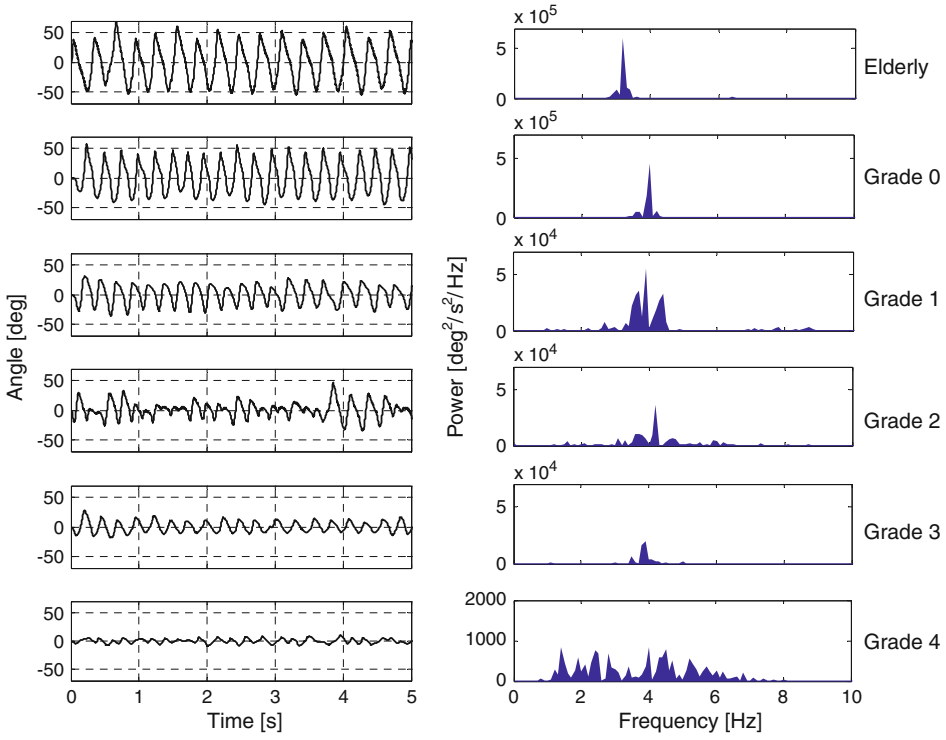

Fig. 3 Typical angle signals from integration of filtered gyrosensor signals and their power spectrums in patients with different finger taps scores as well as in healthy elderly subjects. Angle data for 5 s are shown, whereas 10 s of data were used in the analysis

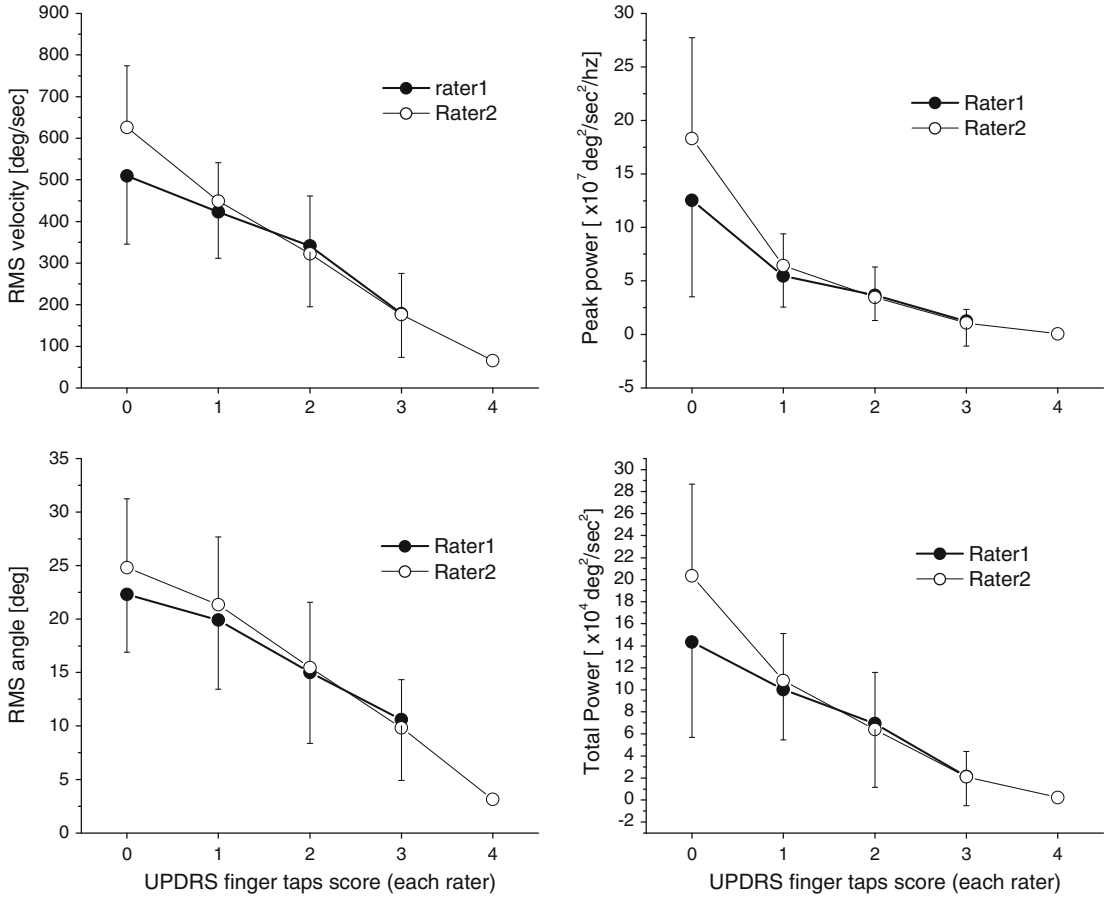

Fig. 4 Relationship between performance indices and clinical finger taps score

significant differences in all PIs among different FT scores ($P < 0.001$) and post hoc tests revealed that PIs could discriminate all or two of three neighboring pairs of FT scores in the case of rater 2, but one or none of neighboring pairs in the case of rater 1 ($P < 0.01$). PIs could discriminate most non-neighboring pairs in both raters ($P < 0.01$). Statistical differences in PIs between a score of 4 and the others were not evaluated because there was only one set of data (by rater 2) classified as score 4 (Table 2).

4 Discussion

The inter-rater reliability of the FT score was acceptable in that Cronbach's alpha was 0.85 and the ICC coefficient was 0.74. The difference in two coefficients indicates that the standard clinical measure may be good in terms of the internal (each rater's) consistency of scoring, but may be not as good in terms of absolute agreement of two raters. The latter was supported by the difference in PI values of two raters (Fig. 4), especially in the lowest FT score, which might be due to the ambiguity between a score of 0, indicating 'normal', and a score of 1, indicating 'mild slowing and/or reduction in amplitude'.

Gyrosensor signals from patients (Fig. 2) showed feasibility for use as a measure of bradykinesia in finger tapping tasks. In a more quantitative aspect, the ability of PIs derived from the gyrosensor to reflect the clinical FT score was evaluated in two ways (Table 1). Regarding the consistency of the relationship between PIs and FT score, correlation coefficients of RMS velocity, RMS angle, and total power with FT score ($r = 0.78$–0.80) were superior compared to the best correlation reported in the literature ($r = 0.63$ [15]). Regarding differentiating ability, all PIs could distinguish patients from control. Moreover, all or two-thirds of neighboring pairs of FT score could be discriminated by PIs in the case of rater 2; however, only one or none of the neighboring pairs could be discriminated in the case of rater 1. This suggests that the PIs of this study could fairly represent the ratings of rater 2 but not those of rater 1, which might be related to the ambiguity of UPDRS addressed as one of the weaknesses in UPDRS [16]. Nevertheless, correlations of mean of FT scores of the two raters with PIs were better than those of each rater's FT

Table 1 Statistical analysis results

Performance indices	Rater ID number	Spearman's correlation coefficient		Difference between subject groups	Difference among different FT scores						
		Mean FT score of two raters	FT score of each rater	Independent *t*-test	ANOVA	Post hoc (Tukey) test					
				Control vs. patients		Neighboring pair			Non-neighboring pair		
						0 vs. 1	1 vs. 2	2 vs. 3	0 vs. 2	0 vs. 3	1 vs. 3
RMS velocity	1	−0.78**	−0.72**	**	**			**	+	**	**
	2		−0.74**		**	+	*	**	**	**	**
RMS angle	1	−0.73**	−0.66**	**	**				+	**	**
	2		−0.70**		**		*	*	+	**	**
Peak power	1	−0.80**	−0.74**	**	**	**			**	**	**
	2		−0.75**		**	**	*	+	**	**	**
Total power	1	−0.78**	−0.72**	**	**			*	*	**	**
	2		−0.73**		**	*	*	*	**	**	**

+ $P < 0.05$, * $P < 0.01$, ** $P < 0.001$

Table 2 Number of data (hands) in each FT score

FT score	Rater 1	Rater 2
0	8	4
1	26	21
2	18	32
3	28	22
4	0	1
Total	80	80

score with PIs (Table 1), suggesting that weakness of UPDRS can be reduced by averaging the FT scores of multiple raters. Peak power had a tendency to differentiate lower FT scores well (e.g., 0 vs. 1) and RMS velocity and total power differentiated higher FT scores well (e.g., 2 vs. 3). This suggests that more than one PI would be beneficial for diagnosis of a wide range of patients.

The above abilities suggest that the new PIs of this study reflect the clinical FT score well and that they are better than any found in the literature. This improvement in performance is thought to be due to the following. First, in contrast to studies found in the literature, where sensors, e.g., potentiometer [13] and accelerometer [18], constrained the natural finger tapping motion, the PIs of this study were derived from the light-weight and gravity-free gyrosensor, so that little constraint was applied to the movement. Second, a gyrosensor measures angular movement, which represents the finger tapping motion better than linear displacement or its derivatives in the literature [1, 9, 18]. Third, action tremor was judged and eliminated upon inspection of the frequency spectrum, which was not attempted in the literature, and this strategy might have improved the reliability of the measured signal and the PIs derived from it.

The sensor system developed in this study was small, light-weight, and easy to use during the clinical finger taps test, so that it is easily applicable in a clinical situation, e.g., in the outpatient clinic as well as at the bedside. It is expected to be useful in the diagnosis of abnormalities of fine motor control and also in evaluation of the effect of medication and deep brain stimulation in a more objective and quantitative way.

In order to be useful for clinical purposes, the system and method suggested in this study should be tested on a large population of normal and pathological subjects, as well as of clinicians, so that normative data and stratification values for different FT grades can be provided. This must be studied further as an extension of this communication.

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