
Myoclonic-like Finger Microdisplacements in Patients With Cerebellar Deficits

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ABSTRACT: Background: Here we assess the ability of patients with cerebellar disease to execute a simple visually-guided movement task involving tracking of a target with the index finger. **Methods:** Spontaneous microdisplacements in index finger position are compared in patients with cerebellar deficits (ischemia [n = 3], multiple sclerosis [n = 3], degenerative cerebellar disease [n = 3]) and age-matched healthy subjects. Subjects were required to maintain a constant finger position relative to a stationary baseline displayed on an oscilloscope. **Results:** Unusual transient abrupt movements (saccadic or myoclonic-like) directed with or against gravity were seen in patients whose neurological deficits were the most severe (7/9 patients). These abrupt myoclonic-like movements occurred independently of visual input, were not associated with clinically observable myoclonus, and were not detected previously in patients with Parkinson's disease. These abrupt myoclonic-like movements were not associated with abnormalities in either physiological tremor, or oscillations in finger microdisplacements induced by insertion of a delay (300-1400 ms) into the visual feedback of this finger "holding" experiment. An unexpected finding is that the results obtained for patients with cerebellar deficits by insertion of an experimental delay are not significantly different from those obtained with their age-matched controls. **Conclusions:** These observations suggest that abrupt myoclonic-like movements are a characteristic abnormality of patients with a variety of cerebellar deficits and emphasize the value of this simple motor tracking task for characterizing movement disorders.

RÉSUMÉ: Microdéplacements pseudo-myocloniques de l'index chez des patients avec atteinte cérébelleuse.

Introduction: Nous évaluons la capacité de patients atteints de déficits cérébelleux d'effectuer un tâche simple, guidée visuellement, dans laquelle le sujet doit suivre une cible avec l'index. **Méthode:** Les microdéplacements spontanés de l'index sont comparés chez des patients ayant des déficits cérébelleux (ischémie [n = 3], sclérose en plaques [n = 3], maladie dégénérative du cervelet [n = 3]) et chez des sujets en santé du même âge. Les sujets devaient maintenir une position constante du doigt en relation avec une ligne de référence fixe présentée sur une oscilloscope. **Résultats:** Des mouvements intermittents et abrupts (saccadiques ou pseudo-myocloniques) ont été observés avec ou contre la pesanteur chez les patients dont les déficits neurologiques étaient les plus sévères (7/9 patients). Ces mouvements abrupts ne sont ni associés à l'observation clinique de myoclonus, ni observés chez des patients atteints de la maladie de Parkinson; et sont indépendants de l'input visuel. Ces mouvements pseudo-myocloniques abrupts ne sont pas associés avec des anomalies du tremblement, ou avec la présence d'oscillations dans les microdéplacements du doigt, associées avec l'introduction d'un délai (300-1400 ms) dans le feedback visuel de cette tâche posturale. Un résultat inattendu est que chez les patients ayant un déficit cérébelleux, l'insertion d'un délai expérimental ne produit pas de résultats statistiquement différents de ceux obtenus avec les sujets contrôles du même âge. **Conclusions:** Ces observations suggèrent que les mouvements pseudo-myocloniques abrupts de l'index représentent une anomalie caractéristique des patients atteints de déficits cérébelleux variés et mettent l'emphase sur la valeur de ce test simple dans la caractérisation des anomalies du mouvement.

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Although disorders of movement can be readily recognized, their precise description at the bedside and in the movement laboratory is notoriously difficult.¹ One approach to overcome this difficulty has been to analyse very simple movement tasks. Perhaps the most widely used are visually guided tasks involving tracking of a target.²⁻⁶ A particularly simple motor task is to hold finger position constant relative to a stationary target under visual guidance.⁷⁻¹⁰ This holding task combines features of postural control and visuomotor tracking since finger position must be continually corrected in response to spontaneous perturbations

due, for example, to physiological tremor and the ballistocardiogram.

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There are two advantages of this finger "holding" paradigm for the study of motor control in health and disease. First, the movements are confined in the vertical plane and can be measured with a high degree of accuracy. Second, it is possible to introduce perturbations, such as different visual delays⁷ and noise perturbations,¹¹ into the visual feedback.

The above observations suggest the possibility of diagnosing and characterizing motor abnormalities in patients with neurological diseases by making measurements at the finger tip. Indeed using this approach, it has been possible in patients with Parkinson's disease to characterize a variety of movement abnormalities¹² and to assess the interplay between delayed visual feedback and noise in motor tracking.¹³

Here we assess the ability of patients with cerebellar deficits to execute this finger "holding" paradigm. A number of anatomical,¹⁴ clinical¹⁵⁻¹⁷ and laboratory^{18,19} observations stress the role of cerebellar mechanisms for the moment to moment control of visually guided movements. Thus, it might be anticipated that our finger "holding" paradigm would be useful for the characterization of abnormalities in visuo-motor control in this patient group.

METHODS AND MATERIALS

Subjects

Eighteen subjects were studied: 9 patients with a cerebellar lesion including 4 women and 5 men (ages 18 to 58, mean age = 39.4 years) and 9 age-matched control subjects (ages 19 to 56, mean age = 39.7 years). The patients presented a spectrum of clinical pathologies ranging from minimal or no impairment (C3, C4, C5) to moderate impairment (C6, C7, C8), to significant difficulties with balance, posture, locomotion and coordination (C1, C2, C9). Patients with moderate or severe signs and

one with mild signs had intention tremor during the finger to nose test. Patients were carefully selected from the large population attending general neurology, multiple sclerosis and cerebrovascular disease clinics. The selection criterion was a predominance of cerebellar symptomatology such as dysmetria and ataxia with an absence of long tract signs such as paresis, increased tone, hyperreflexia, or Babinski reflex. In all cases, cerebellar involvement was confirmed by radiological studies including angiography where appropriate. Patients were excluded if they were unable to do the task because, for example, of severe arthritis or tremor. The clinical characteristics of these patients are summarized in Table 1. The final patient group included 3 patients with ischemia (2 with occlusion of branches of the left superior cerebellar artery and one with basilar artery dissection), 3 patients with multiple sclerosis and 3 patients with degenerative cerebellar disease (one with olivopontocerebellar atrophy, and two of unknown etiology). Handedness was evaluated using the Edinburgh Inventory.²⁰ In this test presented in Table 1, a result of 100% means that the subject is 100% right-handed while a result of -100% means that the subject is 100% left-handed.

The details of the experimental protocol were explained to each subject and then they were asked to sign a consent form. Subjects did not consume caffeinated beverages or medications during the 12 h preceding the experiment. They were tested in the morning and the session lasted about 60 min.

Apparatus

A diagram of the experimental setup is presented in Figure 1. A detailed description of the experimental protocol is given elsewhere.⁷ In brief, Linear Variable Displacement Transformers (LVDT model SE-373/25 and Schaevitz DC-E 1000) were used to record microdisplacements of the metacarpo-phalangeal joint of the index finger (resolution of 0.023 mm). The position of the

Table 1: Characteristics of Cerebellar Patients.

Patient number (signs *)	Age (yrs)	Sex	Handedness (% right)	Time since onset (yrs)	Stability of illness (yrs)	Affected side	Vision problem	Gait and posture problem	Speech problem	RAM **
C1 +++	30	M	100	3	1	L	severe	severe	yes	L
C2 +++	56	F	71	10	5	L	mild	moderate	yes	L
C3 +	18	M	100	2	1	L	mild	none	no	L
C4 +	24	F	100	4	1.5	L	mild	none	no	L
C5 +	34	F	100	2	0.5	L	mild	none	no	L
C6 ++	41	M	-100	16	10	R	moderate	moderate	no	R
C7 ++	49	F	85	20	3.5	R	mild	severe	no	R
C8 ++	58	M	100	6	2	L	moderate	severe	no	L
C9 +++	45	M	-80	27	4	R	mild	severe	yes	R

* severe +++
moderate ++
mild +

** RAM Rapid Alternating Movement (worse side)

finger relative to a stationary horizontal line displayed on an oscilloscope was delayed up to 1400 ms through an analog delay line. After being delayed the signal was filtered using an eight-pole low pass Bessel filter (from Frequency Devices, model 902 LPF) with a corner frequency of 30 Hz. The subjects could not see their index finger directly but could follow the displacements of their finger on an oscilloscope screen which was placed in front of them at a distance of 80 cm. The gain of the oscilloscope (model Phillips PM 3305) was adjusted so that a vertical displacement of 1 mm of the extremity of the index finger corresponded to about 12 mm of vertical displacement on the screen. The signal from the LVDT was sent to an A/D converter (model DT-2821-F-SE 16) connected to an acquisition system (DataWave Technologies) and a 80386-20 based computer (COMPAQ). The sampling rate during data acquisition was 102.4 Hz (i.e., 8192 points for 80 s). The resolution was 4096 A/D points for 5 volts (i.e., 819 A/D points/volt).

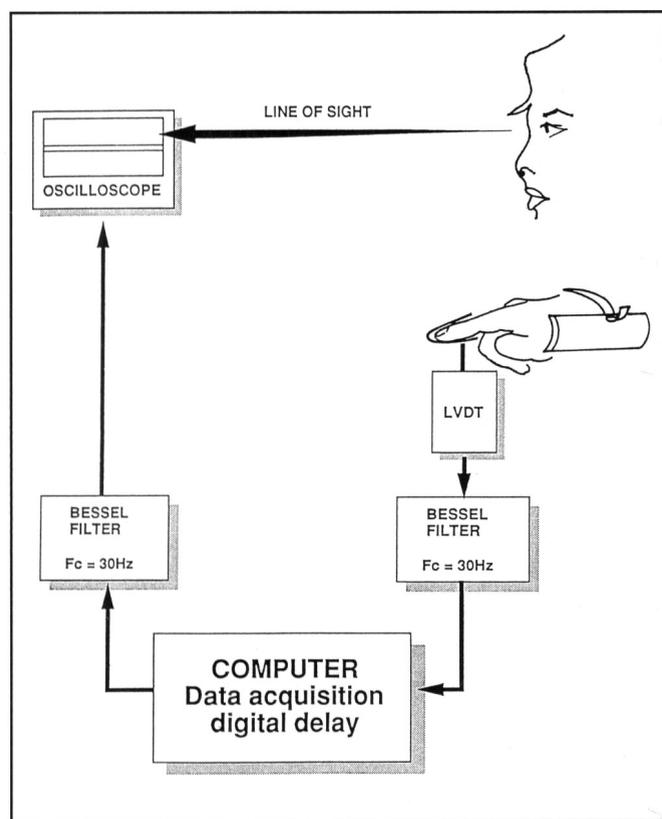


Figure 1: Diagram of the experimental setup.

Test Procedure

Subjects were seated in an upright position and maintained in a stable posture by two seat belts. The tested forearm was supported in a trough with a 90° angle at the elbow. The index finger was extended and a fist was made around the thumb with the three remaining fingers. A medical splint was placed onto the index finger and connected to the LVDT (Figure 1). The subjects were asked to align the oscilloscope line, recorded from their index finger via the LVDT with the stationary target line. Fourteen tests were carried out on each subject: nine on the

more affected side and five on the less affected side. On the more affected side two trials without time delay (first and eighth trials), six trials with a time delay (300, 600, 800, 1000, 1200 and 1400 ms) presented in counterbalanced order, and one trial with eyes closed (ninth trial) were conducted. On the less affected side, one trial without time delay (first trial), three trials with time delays (800, 1000 and 1400 ms) presented in counterbalanced order, and one trial with eyes closed were conducted. These fourteen conditions were also tested in control subjects. Subjects were told that the tracking task would at times become more difficult to perform, but they were not informed that a time delay in visual feedback would be introduced. Each test lasted for 80 s and followed a period of 20 s given to the subjects to familiarize themselves with the condition. A resting period of about 1 minute was given after each test.

Data Analysis

Data analysis was done with software developed in our laboratory in Microsoft QuickBASIC (Version 4.5) and commercial software such as Matlab (PC-Matlab, the Math Works Inc.). Only the last 40 s of data out of 80 s were analyzed to allow the subjects to stabilize their performance. The period of the oscillations was calculated from the raw data. Root Mean Squares (RMS), means, and number of crossings of the mean finger position provided measures of the errors made by the subjects. Fast Fourier Transforms were calculated for the last 40 s of the time series using four sections of 1024 points which were first Hanning windowed and then averaged.

RESULTS

Finger Microdisplacements

Healthy Subjects

Fluctuations in microdisplacements of finger position relative to the stationary target are observed in all subjects (Figure 2a). In 7/9 healthy subjects the amplitude of these fluctuations is smaller on the dominant side. RMS displacements was of 0.24 mm (± 0.09) for the dominant hand, 0.26 mm (± 0.01) for the non-dominant side. The power spectra of these fluctuations show a broad distribution of frequencies without a dominant peak in 6 subjects, and with a distinct peak between 6 and 10 Hz in 3 subjects (not shown).

Patients with Cerebellar Deficits

Data from the patients were systematically compared with that of their age-matched control subjects. Thus, data from S2 for example, are compared with data from subject C2 presented in Figure 2b. As can be seen, this patient has some difficulty staying on the target. Only patients with moderate or severe deficits experienced such instabilities. The analysis of the frequency and amplitude of the fluctuations in finger displacement of patients with cerebellar deficits was made difficult by the presence of an erratically occurring movement abnormality characterized by its abruptness and its unusual morphology (see arrows indicated in Figure 2b). Since these movements are reminiscent of myoclonic-like movements, we refer to them as "Abrupt Myoclonic-Like Movements" (AMLML). These movements resemble "high velocity segments" reported previously.²² They were directed with, or against gravity.

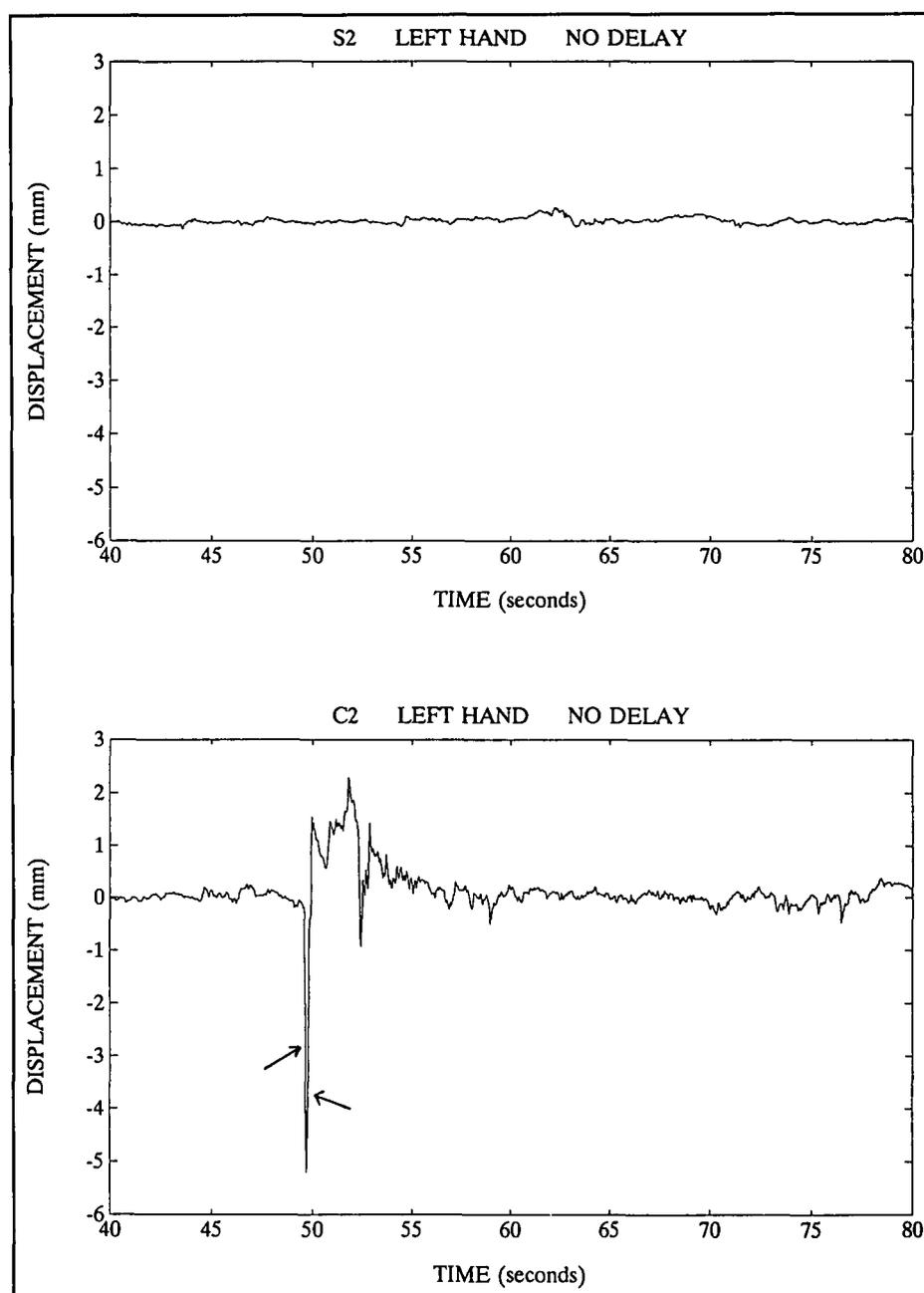


Figure 2: Time series of the last 40 s for the trial performed by subject S2 at 0 ms delay illustrating physiological tremor (a). Time series of the last 40 s for the trial performed by subject C2 at 0 ms delay illustrating physiological tremor (b) and AMLM (→).

We adapted methods used for on-line computer detection of epileptic spikes in the electro-encephalogram to obtain a quantitative description of an AMLM.²³ With this approach, criteria are required to describe the amplitude and velocity of the AMLM (Criteria 1 and 2), to minimize the effect of the fluctuating background on the measurements (Criterion 3), and to guarantee that the event is indeed an abrupt one (Criterion 4). A detailed description of the four criteria we developed to describe AMLM is given in the Appendix. Table 2 demonstrates that all criteria are necessary to faithfully identify all of the AMLM detected by visual inspection. It should be noted that these criteria

are sufficiently robust that they are able to detect AMLM in patients whose physiological tremor is actually smaller than that of the age-matched control subject (see for example, C9 and S9 in Table 2).

With these criteria AMLM were observed in all but 2 patients with cerebellar deficits. The only two patients for whom these AMLM were not observed were C4 and C5 who had very mild cerebellar involvement (Table 1). The number of AMLM ranged from 2 to 9 in one 40 s trial, i.e., their frequency of occurrence ranged from $.05 \text{ sec}^{-1}$ to 0.225 sec^{-1} . No AMLM were detected in the age-matched healthy subjects.

Table 2: Illustration of criteria for detection of AMLM.

SUBJECTS	Max. Vel. (mm/9.8ms*)	Number of Fast Segments**	Corrections for Tremor#	Number of AML#
C2 (0 ms delay)	.3406	15	10	2
S2 (0 ms delay)	.0146	0	0	0
C9 (0 ms delay)	.1831	28	25	9
S9 (0 ms delay)	.0427	0	0	0
C8 (1400 ms delay)	.1001	2	2	2
S8 (1400 ms delay)	.1331	1	1	0
C6 (1400 ms delay)	.2332	5	6	2
S6 (1400 ms delay)	.0757	0	0	0

* digitization unit (9.8 ms)

** a fast segment is one in which the displacement in 39.2 ms (i.e., 4 digitization steps) exceeds three times the standard deviation of four point segments in the matched control subject

See Appendix

The portions of the records which did not contain AMLM were used to characterize the amplitude and frequency of finger microdisplacements in patients with cerebellar deficits. The amplitude of fluctuations due to tremor tend to be higher on the non-dominant side for 8/9 patients with cerebellar deficit (RMS amplitude of 0.341 mm (\pm 0.325) versus 0.335 mm (\pm 0.244) for the dominant and non-dominant side respectively). This observation may be, at least in part, related to the fact that 7/9 of these patients have predominantly non-dominant side symptomatology. Power spectra of these fluctuations reveal a broad distribution of frequencies without a clear dominant peak (not shown).

Added Visual Delay

The introduction of an experimental time delay into this visually guided motor task is known to produce intermittent, large amplitude oscillations in finger displacement in healthy subjects⁷ (Figure 3a). The period of these delay-induced oscillations is between two and four times the added delay, and thus the induced oscillations have a lower frequency content than the spontaneously occurring fluctuations in finger microdisplacement studied in the previous sections. Delay induced oscillations typically appear for delays > 600 ms. These oscillations are thought to arise from the delay induced destabilization of an, as yet unidentified, negative feedback loop.⁸ Although the presence of these oscillations can be readily detected by visual inspection of the time series, their intermittent nature makes quantitative analyses difficult. The presence of abrupt movements was also noted in the trials performed with a time delay (Figure 3b).

Two methods were used to compare delay-induced oscillation in healthy age-matched controls and patients with cerebellar deficits: (1) number of mean crossings; and (2) power spectral analysis.

Mean Crossings

A crossing is defined as a change in sign in the position of the finger relative to the stationary target line, e.g., a crossing occurs when finger position moves from above the target to below.²⁴ In the absence of added delay, the number of crossings for the patients with cerebellar deficits is approximately 40% less than for their age-matched controls (Figure 4a). This is in

part, a consequence of the observation that the mean amplitude of the fluctuations is higher in the patient group (Figure 2). Overall, the number of mean crossings decreased significantly as the added delay increased for both groups [$F^{2,32} = 20.34$, $p < 0.05$]. This decrease in mean crossings reflects the presence of an oscillation with a longer frequency which decreases with increasing delay. To better assess the effect of added delay, we normalized the number of mean crossings to the number observed with no added delay (Figure 4b). As can be seen in Figure 4b there is no significant difference between the two groups.

Power Spectral Analysis

A delay induced low frequency oscillation is reflected by an increase in the relative power corresponding to frequencies $1/4\tau$ and $1/2\tau$, where τ is the time delay (see change in scale from 60 to 1000 on the vertical axis, for frequencies below 2 Hz in Figure 5). As is shown in Figure 5, an increase in relative power in the expected frequency range with added delay occurs. The expected increase in low frequency power with increased delay was seen even for time series which, on visual inspection, did not appear rhythmic. In view of these observations we concluded that patients with cerebellar deficits behaved normally with respect to this task. We verified that for all patients with cerebellar deficits and their age-matched controls, a delay-induced increase in relative power in the expected frequency range occurred.

The number of mean crossings decreased as the added delay increased for cerebellar patients as was observed for healthy subjects. The decrease in the number of mean crossings is about 31% on the right side and 54% on the left side of patients with cerebellar deficits (Table 2). For these calculations the last 40 seconds of each trial were used.

The decrease in the number of mean crossings as the added delay increased was mirrored by an increase in the relative power in the expected low frequency range of the power spectra (below 2 Hz).

Eyes Closed

The execution of the finger holding paradigm with eyes closed produced highly variable results over 80 s. Some subjects remained stable or drifted upwards while others drifted down-

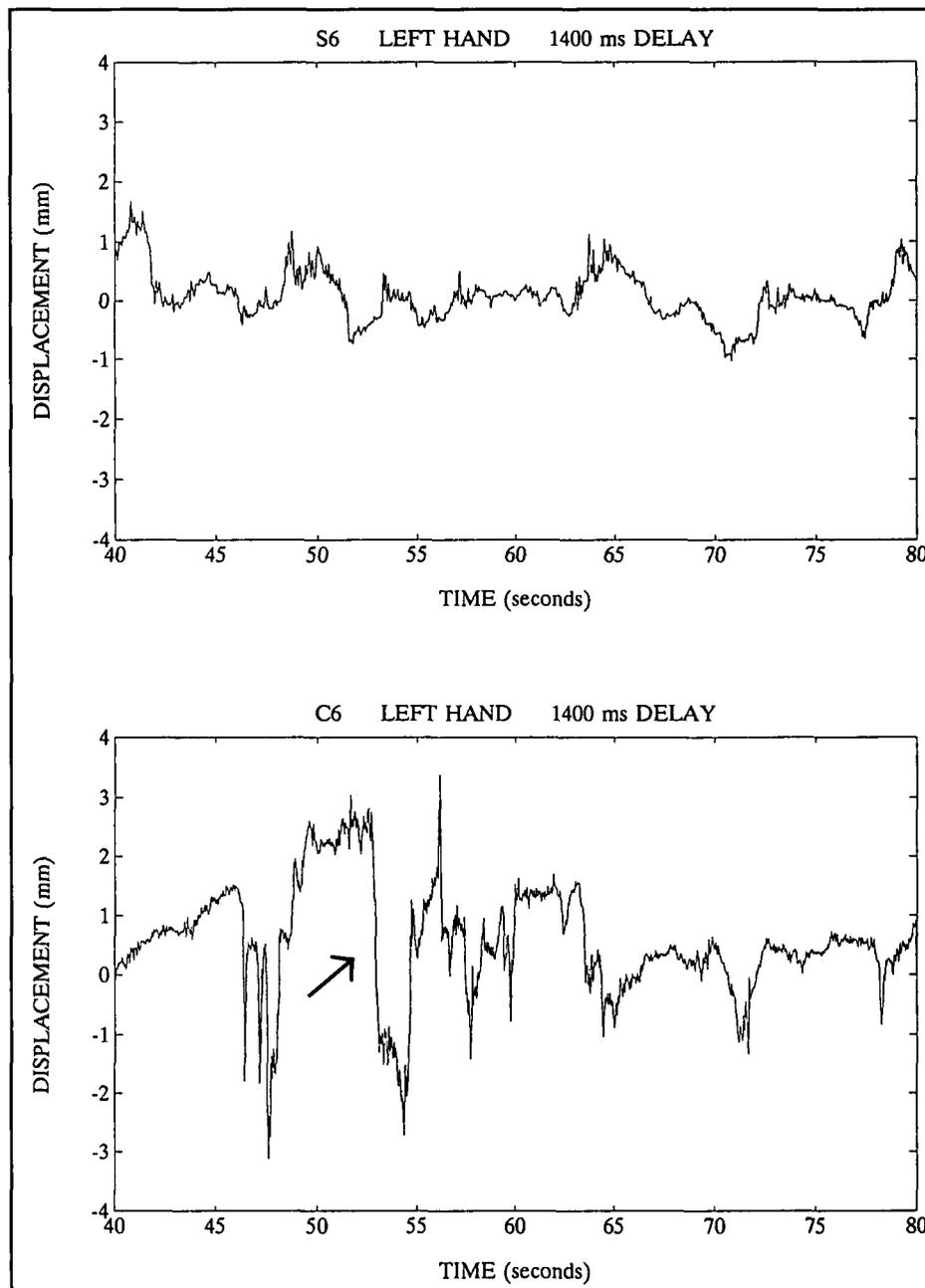


Figure 3: Time series of the last 40 s for the trial performed by subject S6 at 1400 ms delay illustrating physiological tremor and large amplitude low frequency oscillations (a). Time series of the last 40 s for a trial performed by patient C6 illustrating AMLM (indicated with an arrow) recorded at 1400 ms delay (b).

wards. The fact that finger position drifts away from the stationary target emphasizes the role played by visual feedback in this task, for control subjects and patients with cerebellar deficits. AMLM were observed in two patients with cerebellar deficits indicating that this phenomenon is not dependent on visual feedback.

DISCUSSION

Here we have examined the dynamics of finger displacement during a visually guided tracking task. The most characteristic abnormality we observed in patients with cerebellar deficits was

the presence of high velocity segments or abrupt "myoclonic-like" movements (AMLM). Pseudo myoclonic jerks occur in subjects who attempt to perform slow and smooth maneuvers.²¹ However, the fact that we did not observe the AMLM for healthy subjects suggest that these two phenomena may not be the same. AMLM have been observed in wrist movements of patients with cerebellar incoordination.²²

Qualitatively the high velocity segments are reminiscent of myoclonic muscle movements or micro-saccadic eye movements observed in patients with cerebellar deficits. The association of myoclonus and cerebellar disease is most typically seen in

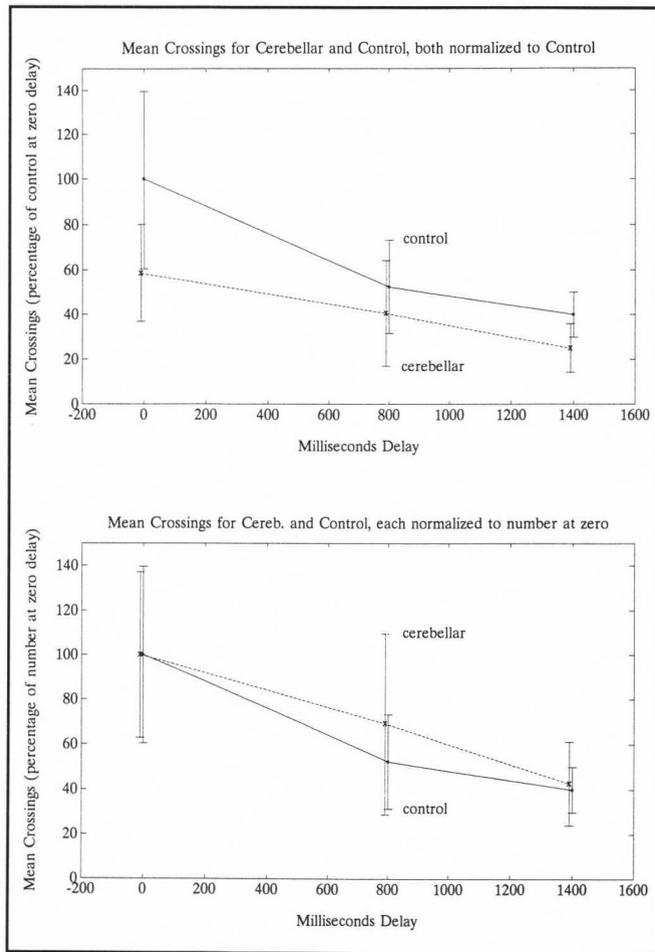


Figure 4: Number of mean crossings for control subjects (.) and patients with cerebellar deficits (x) at zero, 800 and 1400 ms delays. (a) both traces are normalized to control values; and (b) both traces are normalized at zero. Error bars are also indicated.

patients with extensive brainstem and cerebellar pathology as occur in, for example, spinocerebellar degenerative disease, Lafora disease, Creutzfeld-Jacob disease, neuroblastoma and Ramsey Hunt syndrome. The patients we studied were chosen because their pathology was localized primarily to the cerebellum. The fact that AMLM, albeit of small amplitude and relatively short duration, can be observed in 7/9 patients suggests that the cerebellum plays a role in their generation. It has been previously suggested that abnormalities in limb movements might be related to deep cerebellar nuclei damage.¹⁹ However, one cerebellar patient in whom we did not observe AMLM was a patient who had a thrombosis of the hemispheric branches of the left cerebellar artery. This artery often provides a single superior vermian artery and some of its branches extend to the deep cerebellar nuclei.¹⁶ In the present study, patient C4 performed the task as well as control subjects (i.e., stable and low amplitude fluctuations at no delay and low frequency oscillations with high delays, etc.). Thus, in subject C4 the deep cerebellar nuclei were either spared or only slightly affected. The other subject, C5, had had ischemia with possible dissection at the top of the basilar artery, but clinical examination at the time of testing was normal in terms of tracking, gait and posture.

The quantitative description of abrupt events with varying mor-

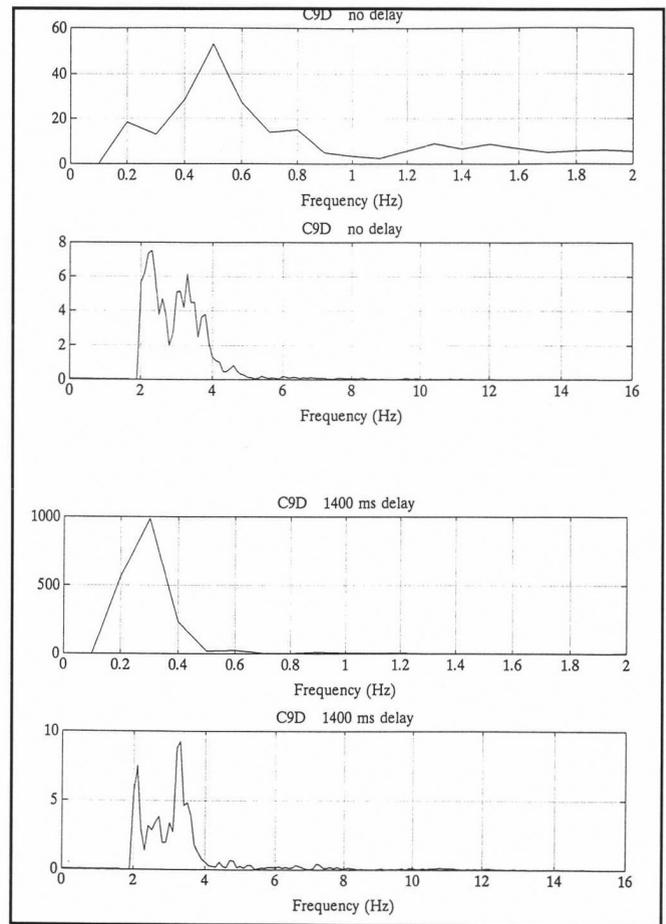


Figure 5: Comparison of the power spectra of patients C9 at zero delay (above) and C9 at 1400 ms (below). For each trial, the top plot represents the power between 0 and 2 Hz, and the bottom plot represents the powers between 2 and 16 Hz. Note the difference in scale between the two conditions.

phology is problematic and at present no technique exists which is better than visual inspection by an experienced human observer.³¹ A problem is that the simple approach of describing an abrupt event in terms of its velocity and displacement becomes rapidly obscured as additional criteria are added, which ensure that the observed changes have not arisen by chance. Thus, quantitative criteria, such as those we developed for AMLM and those developed previously for epileptic spikes,²³ are typically not as illuminating as what the mind sees on visual inspection of the record (e.g., Figure 3b). It is unlikely that the use of other approaches to quantitate abrupt events, such as wavelet analysis³² would alleviate this problem. Thus, we anticipate that our criteria for an AMLM would be of little use diagnostically where the key issue is simply whether or not an AMLM occurs rather than the exact number. On the other hand, should long term monitoring of finger micro-displacements become important (i.e., drug trials) then the criteria we have developed appear to be adequate.

The appearance of a low frequency oscillation in tracking error when the visual delay is increased is thought to arise from the destabilization of negative feedback control loop(s) by the increased delay.^{7,8} However, the identity of the control loop(s) which become(s) destabilized is unknown. Visual delay induced

oscillations with the expected period, i.e., two to four times the added delay, are observed in patients with Parkinson's disease¹³ and in patients with cerebellar deficit (this study). These observations suggest that the basal ganglia and cerebellum do not play dominant roles in the control loop(s) which becomes destabilized by the increased visual delay. A curious finding was that the delay-induced low frequency oscillation in finger microdisplacements was observed at some delays, but not at others, in the same subject. Even though the oscillation was not visually obvious, it was readily detected by an increase in power in the relevant frequency range. There was no clear relationship between the absence of an oscillation, the occurrence of AMLM or the severity of the cerebellar symptomatology.

Many authors have stressed the importance of the cerebellum in the moment to moment control of visually guided movements.¹⁸ Previous studies have shown that in patients with cerebellar damage, visual reaction times¹⁵ and motor preparation¹⁷ are delayed. Although our experimental paradigm emphasizes the role of visual feedback and delay for making precise movements we did not observe an increase in intention tremor. This observation contrasts with current hypotheses on the mechanism of intention tremor which stress the role of visual input.^{25,27} In this last study,²⁷ the effect of temporarily suppressing the visual display of either the target (desired) trajectory or the actual movement trajectory decreased the accuracy of visuo-motor tracking in patients with cerebellar disorders. However, an independence of intention tremor on visual input has been reported previously.^{26, 27}

Visual tracking of the target with the index finger requires that the necessary movement(s) be planned, programmed and then executed.^{28,29} Although simple, these tasks are sufficiently demanding to be able to uncover a variety of abnormal movements which appear to have some localizing value. Abnormalities in eye movements are well known to be useful for localizing pathology within the relevant neural pathways which control eye movement.³⁰ In Parkinson's disease, visual tracking of the index finger with or without delay, revealed that patients with the kinetic form of the disease had a variety of abnormal finger movements and no large amplitude low frequency oscillations.¹³ It is hoped that by the use of simple, well defined motor tasks, the careful introduction to this paradigm, the careful selection of patients and the development of appropriate mathematical models, we will be able to unravel the essential properties of the mechanisms controlling this simple movement task and improve its clinical utility.

APPENDIX

The computerized criteria used to detect an AMLM are:

(1) Criterion 1 identifies the distance traversed over four consecutive digitized points and determines whether this distance is larger than three times the standard deviation of the distance traversed over four points for the matched control subject. This standard deviation is calculated from the distances between points 1 and 5, points 2 and 6, points 3 and 7, etc.

(2) Criterion 2 identifies whether the distance between four points is contained in a larger high velocity segment. To achieve this, the program looks for segments with one tremor beat on both sides of the four-point distance. The presence of tremor is indicated by a change of slope which goes through zero. If two

segments occur side by side, they are grouped as one.

(3) Criterion 3 minimizes the effect of tremor on the measurements. The total distance of the section must be larger than four times the standard deviation of the microdisplacements of the matched control subject.

(4) Criterion 4 consists in taking the best fit line (determined by least squares analysis) through the section identified by the above criteria, and for the one second of data preceding the identified segment. The ratio of the two slopes (i.e., slope preceding over section slope) must be less than a critical value fixed at 0.05. Extreme values or zero suggest a drastic or abrupt change in the morphology of the oscillations.

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REFERENCES

1. Fahn S. The varied clinical expressions of dystonia. *Neurol Clin* 1984; 2: 541-554.
2. Flowers K. Lack of prediction in the motor behaviour of parkinsonism. *Brain* 1978; 101: 35-52.
3. Flowers K. Some frequency response characteristics of parkinsonism on pursuit tracking. *Brain* 1978; 101: 19-34.
4. Moore AP. Impaired sensorimotor integration in Parkinsonism and dyskinesia: a role for corollary discharge? *J Neurol Neurosurg Psychiatry* 1987; 50: 544-552.
5. Warabi T, Noda H, Yanagisawa N, et al. Changes in sensorimotor function associated with the degree of bradykinesia of Parkinson's disease. *Brain* 1986; 109: 1209-1224.
6. Abdel-Malek A, Markham CH, Marmarelis PZ, et al. Quantifying deficiencies associated with Parkinson's disease by use of time-series analysis. *Electroencephalogr Clin Neurophysiol* 1988; 69: 24-33.
7. Beuter A, Larocque D, Glass L. Complex oscillations in a human motor system. *J Mot Behav* 1989; 21: 277-289.
8. Glass L, Beuter A, Larocque D. Time delays, oscillations and chaos in physiological control systems. *Math Biosci* 1988; 90: 111-125.
9. Merton PA, Morton RA, Rashbass C. Visual feedback in hand tremor. *Nature* 1967; 216: 583-584.
10. Smith KU, Putz V, Molitor K. Delayed retinal feedback of eye movements: a dynamic basis of perceptual disabilities. *J Appl Psychol* 1970; 54: 538-548.
11. Vasilakos K, Beuter A. Effects of noise on a delayed visual feedback system. *J Theor Biol* 1993; 165: 389-407.
12. Beuter A, Labrie C, Vasilakos K. Transient dynamics in motor control of patients with Parkinson's disease. *Chaos* 1991; 1, 3: 279-286.
13. Beuter A, Milton J, Labrie C, et al. Delayed visual feedback and movement control in Parkinson's disease. *Exp Neurol* 1990; 110: 228-235.
14. Brodal A. *Neurological Anatomy in Relation to Clinical Medicine*. New York: Oxford University Press, 1981.
15. Holmes G. The symptoms of acute cerebellar injuries due to gunshot injuries. *Brain* 1917; 40: 461-535.
16. Gilman S, Bloedel JR, Lechtenberg R. *Disorders of the Cerebellum*. Philadelphia: F.A. Davis Company, 1981.
17. Diener HC, Dichgans J, Guschlbauer B, et al. The coordination of posture and voluntary movement in patients with cerebellar dysfunction. *Mov Disord* 1992; 7: 14-22.
18. Stein JF, Glickstein M. Role of the cerebellum in the visual guidance of movement. *Physiol Rev* 1992; 72: 967-1017.

19. Miall RC, Weir DJ, Stein JF. Visuo-motor tracking during reversible inactivation of the cerebellum. *Exp Brain Res* 1987; 65: 455-464.
20. Oldfield RC. The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia* 1971; 9: 97-113.
21. Young RR, Hagbarth KE. Physiological tremor enhanced by manoeuvres affecting the segmental stretch reflex. *J Neurol Neurosurg Psychiatry* 1980; 43: 248-256.
22. Morrice BL, Becker WJ, Hoffer JA, et al. Manual tracking performance in patients with cerebellar incoordination: effects of mechanical loading. *Can J Neurol Sci* 1987; 17: 275-285.
23. Gotman J, Gloor P. Automatic recognition and quantification of interictal epileptic activity in human scalp EEG. *Electroencephalogr Clin Neurophysiol* 1976; 41: 513-529.
24. Bendat JS, Piersol AG. *Random Data: Analysis and Measurement Procedures*. New York: John Wiley & Sons, 1986.
25. Beppu H, Nagaoka M, Tanaka R. Analysis of cerebellar motor disorders by visually-guided elbow tracking movement. *Brain* 1987; 110: 1-18.
26. Flament D, Vilis T, Hore J. Dependence of cerebellar tremor on proprioceptive but not visual feedback. *Exp Neurol* 1984; 84: 314-325.
27. Cody FWJ, Lovgreen B, Schady W. Increased dependence upon visual information of movement performance during visuo-motor tracking in cerebellar disorders. *Electroencephalogr Clin Neurophysiol* 1993; 89: 399-407.
28. Schieber MH. How might the motor cortex individuate movements? *Trends Neurosci* 1990; 13: 440-445.
29. Bizzi E, Mussa-Ivaldi FA, Giszter S. Computations underlying the execution of movement: a biological perspective. *Science* 1991; 253: 287-291.
30. Miller NR. *Walsh and Hoyt's Clinical Neuro-Ophthalmology*. Baltimore: Williams & Wilkins, 1985; 2: 608-784.
31. Gotman J. Computer-assisted EEG analysis. *In*: E. Wyllie, ed. *Treatment of Epilepsy: Principles and Practices*. Philadelphia: Lea and Febiger, 1993, 268-277.
32. Schiff SJ, Milton JG, Heller J, Weinstein SL. Wavelet transforms and surrogate data for electroencephalographic spikes and seizure localization. *Opt Eng* 1994; 33: 2162-2169.