FORCE PLATFORM RECORDINGS IN THE DIAGNOSIS OF PRIMARY ORTHOSTATIC TREMOR.

Kielan Yarrow[1] MSc, Peter Brown[1] MD, Michael A. Gresty[1] PhD, Adolfo M. Bronstein[1] MD.

[1]MRC Human Movement and Balance Unit, National Hospital for Neurology and Neurosurgery, 8-11 Queen Square, London WC1N 3BG, UK

Correspondence to Adolfo M. Bronstein, MRC Human Movement and Balance Unit, National Hospital for Neurology and Neurosurgery, 8-11 Queen Square, London WC1N 3BG, United Kingdom

Phone: +44 (0)20 7837 3611 x 4112

Fax: +44 (0)20 7837 7281

Email: a.bronstein@ion.ucl.ac.uk

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Abstract

Primary orthostatic tremor (OT) consists of rhythmical muscle contractions at a frequency of around 16 Hz, causing discomfort and/or unsteadiness while standing. Diagnosis has hitherto relied on recording EMG from affected muscles. The main aim of this study was to see if the characteristic postural tremor in OT can be identified with force platforms. We also quantified postural sway in OT patients to assess their degree of objective unsteadiness. Finally, we investigated the time relations between bursts of activity in the various affected muscle groups. Subjects stood on a force platform with concurrent multichannel surface EMG recordings from the lower limbs. Seven patients with clinical and EMG diagnosis of OT were examined and the force platform data compared with those of 21 other neurological patients with postural tremor and eight normal controls. All OT patients had high frequency peaks in power spectra of posturography and EMG recordings (12-16Hz). No such high frequency activity was evident in patients with Parkinson's disease, cerebellar degenerations, essential tremor or in healthy controls. Additionally, OT patients showed increased sway at low frequencies relative to normal controls, suggesting that the unsteadiness reported by OT patients is at least partly due to increased postural sway. Examination of EMG timing showed fixed patterns of muscle activation when maintaining a quiet stance within but not across OT patients. These data show a high correlation between EMG and posturography and confirm that OT may be diagnosed using short epochs of force platform recordings.

Introduction

Primary orthostatic tremor (OT) [1] consists of rhythmical muscle contractions at the relatively high frequency of 12-18 Hz. It typically occurs in the legs during stance, with partial or complete cessation of tremor when walking or sitting. There is some controversy in the literature regarding whether OT should be considered a variant of essential tremor, or a diagnostic entity in its own right [2-5]. The former position is based upon an atypically high incidence of upper limb tremor in OT patients, as well as a tendency towards essential tremor diagnoses in first-degree relatives. However, these associations are not observed in all OT patients. Further, OT patients often exhibit a pattern of response to pharmacological treatment that is different to that of essential tremor; the response to propranolol and primidone is less satisfactory for OT and, unlike essential tremor, some patients may respond to levodopa [6].

A diagnosis of OT is usually reached based on a clinical evaluation in conjunction with electrophysiological investigation using surface EMG [7]. Misdiagnosis can occur in neurootology ('dizziness') clinics because clinicians may not be familiar with this condition [8]. Indeed most of the patients we have seen had been initially diagnosed as suffering from a non-organic (psychogenic) disorder of balance. The primary aim of this study was to see if the characteristic postural tremor in OT could be identified using force platforms, because these devices are often available in neurootology clinics. Accelerometer recordings have previously been taken from OT patients [2,4], but identifying a tremor of an identical frequency to that obtained using surface EMG has not always been possible [2]. In the current study, force platform frequency spectra from OT patients were individually compared with those produced by patients with other conditions with a tremulous stance to see if the findings were specific for OT.

A second unresolved question relates to the actual degree of unsteadiness experienced by OT patients. Patients often report that after a short period of quiet stance they feel they will fall if they do not initiate movement or sit down. However, it is not entirely clear that they actually exhibit more unsteadiness at the low frequencies likely to cause falls (certainly, the incidence of falls has not been reported to be high). Previous research [9] indicates that for normal controls, neuropathic patients and parkinsonian patients, subjective ratings of unsteadiness predict actual body sway well. The current study attempted some quantification of sway at different frequencies to determine whether OT patients are objectively more unsteady than age matched controls.

Finally, the current study permitted a supplementary investigation of muscle firing patterns during quiet stance. In general, the techniques used to investigate patterns of muscle firing have been fairly crude to date [7]. An exception is a recent study that looked in detail at patterns of muscle firing activity for a variety of stances maintained by five OT patients [10]. Patterns were found to be highly consistent for a given patient in a given stance, but to vary between different stances and in different patients. In the current study, precise estimates of muscle firing times were obtained to confirm this finding, including a comparison of the same stance under differing conditions of sensory feedback (eyes open versus eyes closed).

Materials and methods

Subjects

A total of 37 subjects participated in the study. Of primary interest were a group of seven patients with clinical and EMG diagnosis of OT (six female, mean age 63, range 30-80 years) and an additional female OT patient who was diagnosed with the condition by us during the course of the study (age 75). For comparison, data were obtained from 10 patients

with cerebellar degeneration (six female, mean age 59, range 50-68 years), four Parkinsonian patients (two female, mean age 56, range 39-67 years), six patients with essential tremor (four female, mean age 64, range 54-75 years), one patient with psychogenic tremor and jerks (female, 57 years old) and eight healthy controls (seven male, mean age 57, range 49-81 years). Six out of seven previously diagnosed OT patients were taking medication for the condition, but were asked not to take it on the day of testing. One patient failed to comply with this request. All other patients were tested on their medication, usually standard anti-Parkinsonian agents.

Apparatus

Displacements of the centre of force of the standing subject in sagittal and coronal planes were recorded using a force platform. The platform was mounted on four piezo-resistive force transducers in rectangular configuration. Displacements of the net force on the platform were obtained through differential amplification of opposing pairs of transducers. EMG recordings were taken using two silver/silver chloride surface electrodes placed over the belly of the relevant muscle. EMG signals were amplified and filtered using Digitimer D150 Amplifiers. All signals passed through an analogue to digital converter (12 bit; National Instruments MIO16) for storage on a digital computer, and were processed off line (Matlab, The Mathworks, Inc.).

Procedure

Subjects stood on a force platform with their hands hanging by their sides. Quiet stance was maintained for 2 minutes (maximum), or as long as could be managed (> 20 seconds in all cases). Subjects were recorded in each of two conditions: with eyes open, and with eyes closed. For the seven OT patients previously diagnosed, multichannel EMG

recordings were taken from the quadriceps, hamstring, tibialis anterior and gastrocnemius of each leg. Where standing alone proved impossible, subjects were provided with minimal support from the experimenters and/or metal supports enclosing the posturography apparatus. Such support was required by 3/10 cerebellar patients in the eyes open condition, 5/10 cerebellar patients in the eyes closed condition, 3/8 OT patients in both the eyes open and eyes closed conditions, and the patient with psychogenic tremor and jerks in both conditions.

Data Analysis

All signals were sampled at 1000 Hz. EMG signals initially underwent analogue band pass filtering, using a low-pass filter with a high frequency cut-off of 300 Hz (to avoid signal aliasing) and a high-pass filter with a cut-off equivalent to a filter with a time constant of 3 milliseconds (to minimise movement artefact). Posturography data were calibrated by converting signals to Newton meters, then normalising according to subjects' weights to provide centre of foot pressure deviation values in cm or mm.

For analyses relevant to the diagnostic value of the force platform (comparisons of power spectra), these signals were split into overlapping 4096 point data segments, then linearly detrended and multiplied by a Hanning windowing function. Frequency spectra were produced by applying an FFT algorithm to each segment, then averaging; this process yielded power spectral density functions with a maximum frequency of 500 Hz and a frequency resolution of 0.244 Hz. EMG data were calibrated and rectified, then passed through a leaky integrator prior to application of the same FFT. Leaky integration was performed by applying the formula: $Y_n = X_n + \sum_{j=1}^{n-1} 0.9^j X_{(n-j)}$. To assess the degree of agreement between EMG and force platform data (for the seven OT patients with a prior diagnosis only) squared coherence values were obtained between each EMG signal and both directions of sway at the frequency

of tremor. Coherence functions were produced in a manner identical to that previously described for power spectral density functions.

For analyses relevant to the quantification of low frequency sway, overlapping 50000 point segments were used to produce frequency spectra with a frequency resolution of 0.02 Hz. Where signals were under 50 seconds in length (because subjects could not stand for this length of time), they were zero-padded to length 50000 prior to application of the FFT. For each subject, sway magnitude was calculated in frequency bands of 0.02-2, 2-4, 4-10 and 10-30 Hz. This power in band was calculated by taking the average magnitude at all frequency bins within the relevant band; these values were used to compare sway across normal, OT and cerebellar groups. The cerebellar group was included as a control population known to exhibit severe postural instability. The particular divisions chosen reflect: 1) Low frequency sway of potential relevance to unsteadiness and falls (0-2 Hz), 2) A band containing typical tremulous activity for cerebellar patients (2-4 Hz), 3) High frequency tremor activity found only in OT (10-30 Hz) and 4) A 4-10 Hz band, included to make the comparison of sway across frequencies continuous.

Finally, for analyses relevant to the timing of muscle activity in our previously diagnosed OT patients, cross spectra were used to obtain estimates of the timing of cyclical muscle firings relative to sagittal sway as a baseline. These cross-spectral density functions were based on overlapping 4096 point segments, with a frequency resolution of 0.244 Hz. Estimates of muscle timing were based on phase shifts of the cross spectra for all possible combinations of EMG and sway signals. Cross spectra were obtained for each of the eight recorded muscles and two directions of sway in combination with all nine other muscle/sway signals to produce 90 delay estimates (one for each signal relative to all other signals). Nine of these estimates directly described each muscle's (and coronal sway's) delay relative to sagittal sway. These values were added to the remaining 81 delays, such that each became an

additional estimate of a particular signal's delay relative to sagittal sway. For example, the delay between coronal sway and sagittal sway can be found by adding the delay between coronal sway and the right gastrocnemius to the delay between the right gastrocnemius and sagittal sway. These phase shifts at the patient's OT tremor frequency were then averaged so as to obtain a single grand average delay (and standard deviation) for each muscle relative to sagittal sway. Patterns of delays (the nine values obtained for each patient in each visual condition) were correlated with one another (Pearson correlation coefficient) to assess their degree of consistency; this process is more fully described in the results section.

Results

1. Force platform and EMG identification of tremor peaks: case by case comparison

Figure 1 shows some raw EMG traces, alongside their frequency spectra, for four patients. The trace at the top comes from an OT patient; it is possible to count 16 bursts in the one second long trace, confirmed by the 16 Hz peak in the frequency spectrum. Figure 2 shows example posturography traces, again alongside their frequency spectra, for the same four patients. While interpretation of the raw time domain signals is less clear cut, the frequency spectrum for the OT patient once again shows a peak at the frequency of tremor.

Figure 1 near here

Figure 2 near here

Table 1 near here

Table 1 provides an overview of the diagnostic success of EMG and force platform data for our seven previously diagnosed OT patients. Force platform analysis was not fully

conclusive for only a single patient (AV), who was also difficult to diagnose using EMG data. While his frequency spectra did not show striking peaks, 'bumps' were nonetheless evident centred about the frequency of tremor. For all seven OT patients, coherences at the frequency of tremor between muscles and sagittal/coronal sway signals were also generally very high, with a mean of 0.81 (S.D. 0.21).

Figure 3 near here

Frequency spectra of sagittal and coronal sway were inspected for all subjects. Of the 29 non-OT patients and normal controls we tested, only one, with Parkinson's disease, showed a similar substantial peak in the OT frequency range. The frequency spectrum for the sagittal sway of this PD patient is shown in figure 3, above an equivalent frequency spectrum for one of the OT patients. In this PD patient, the peak at 15 Hz was clearly the fourth harmonic of a lower frequency sway peak (harmonics appear at integer multiples of the fundamental frequency, and on this occasion exhibited a pattern of decreasing power with increasing frequency). As such, the pattern of peaks was easily distinguishable from the peaks evident in the OT patients we tested. While their frequency spectra sometimes exhibited sub-harmonics, the high frequency peak in the OT range always stood out relative to any lower frequency peaks.

2. Quantification of sway: group by group comparison

Figure 4 displays average frequency spectra of sway for the OT, normal control and patient control (cerebellar) groups, for sagittal sway with eyes open (N = 8 in each group; data from two of our ten cerebellar patients was not used for technical reasons). Generally, at low frequencies ($\approx<$ 2 Hz) the cerebellar group appeared more unstable than the OT group, who in turn were more unsteady than normals, while at higher frequencies ($\approx>$ 5 Hz) the OT

group showed more activity than both the cerebellar and normal groups, which seemed to converge.

Figure 4 near here

For statistical analysis, absolute sway (mm/Hz) was averaged in each of four frequency bands (0.02-2, 2.02-4, 4.02-10 and 10.02-30 Hz). Data were further subdivided according to patient group (normal, cerebellar and OT), visual feedback (eyes open versus eyes closed) and direction of sway (sagittal versus coronal). Even following logarithmic transformation, the data exhibited extreme heterogeneity of variance, so non-parametric procedures were used in place of a standard ANOVA.

Table 2 near here

A separate Kruskal-Wallis one-way ANOVA was applied to investigate differences between the three patient groups for each combination of visual feedback (two levels), direction of sway (two levels) and frequency band (four levels), for a total of sixteen such tests. All sixteen showed a significant overall difference between groups ($p < 0.05$).[a] Individual group differences where investigated using Kruskal-Wallis follow-ups, again with an adjustment for the number of comparisons run. Table 2 presents the results of four of these comparisons, alongside means and variances, for the three groups' sagittal sway recorded with eyes open. Table 2 supports the earlier observation made regarding figure 4; in general, OT patients showed significantly more sway than normal controls at both low and high frequencies. Their level of sway at low frequencies was in fact more comparable to that of cerebellar damaged patients (whose sway declines to normal levels at higher frequencies). The pattern of significance displayed was fairly similar for sagittal sway with eyes closed, and for coronal sway with eyes open or closed, so no detailed results are presented here.

[a] The omnibus error rate was set at 0.05 for all sixteen tests using a multistage Bonferroni procedure (the Holm procedure; required significance is adjusted based on the number of comparisons still to be run) [11].

3. Relative timing of muscle firings in OT

For all seven previously diagnosed OT patients, the position of each recorded muscle's activation relative to sagittal sway (taken as an arbitrary baseline) was calculated. Figure 5 shows these data schematically for one patient. Note the cyclical (continuous) nature of the data; all muscles fired continuously at the frequency of tremor, but at slight delays relative to one another. These delays were generally constant over the course of the two-minute recordings.

Figure 5 near here

The degree to which patterns of muscle firing were consistent within/between OT patients was assessed by means of the Pearson correlation coefficient. Within-subject consistency was assessed by correlating the pattern of muscle activity obtained during the eyes open condition with that obtained during the eyes closed condition. For between-subject consistency, eyes open and eyes closed data from a particular patient were correlated with the identical condition in each of the other patients. Correlations were based on patterns of nine values (eight muscles plus coronal sway). As an example, for patient MB, whose pattern of activity with eyes open is shown in figure 5, the pattern of delays relative to sagittal sway is (maintaining the ordering of figure 5): 11 ms for coronal sway, then 46, 37, 51, 40, 62, 39, 51and 35 ms for the eight muscles. When tested with eyes closed, MB's muscles fired with the following delays relative to sagittal sway: 12 ms (coronal sway), 41, 33, 47, 36, 60, 35, 46 and 27 ms (muscles). It is apparent that across these two conditions, the overall pattern (from first firing muscle to last firing muscle) is maintained. Correlating the two patterns yields the value 0.99, confirming that MB is producing a consistent pattern across the eyes open/closed conditions.

Problems can occur when using the correlation coefficient to assess data that "loops". In figure 5, from a patient with tremor at 16 Hz, a hypothetical muscle spike at 61

milliseconds would be very close to one at 2 milliseconds; the correlation coefficient will not recognise this fact, and the resulting correlation will be spurious. For this reason, patterns of muscle timing were visually inspected to identify potential problems of this kind. In two patients, one muscle was found to be firing at a delay very close to zero milliseconds relative to sagittal sway. In these two cases, the delay was examined in both the eyes open and eyes closed conditions. When it was very small (around 1 or 2 milliseconds) as opposed to very large (approaching 62.5 milliseconds, the period of tremor for these two patients) a new delay value was obtained by adding the original delay to the overall period of the tremor. Hence, for the two patients in question values of 0 and 1 milliseconds were converted to values of 62.5 and 63.5 milliseconds respectively. Following these two adjustments, all remaining delays were in excess of 10 milliseconds, and were retained.

Figure 6 displays the correlations obtained by comparing each OT patient's muscle activation pattern for a given visual condition (eg eyes open) with that for the alternate visual condition (eg eyes closed). This provides a test of within subject pattern consistency under differing visual conditions (see central non-shaded section in Figure 6). Figure 6 also displays the correlations obtained by comparing each subject's muscle activation pattern for a given condition of visual feedback (eyes open or eyes closed) with the pattern obtained from each of the other OT patients in the identical condition of visual feedback. This provides a test of between subject pattern consistency. The data in Figure 6 show that, for six of the seven patients, there was very high consistency between the patterns of muscle activity in each visual condition. The correlations between different subjects (shown in grey in figure 6) were far more variable, and did not suggest a standard pattern across OT patients.

Figure 6 near here

Discussion

The main purpose behind this investigation was the establishment of the frequency analysis of posturography data as a protocol for the rapid diagnosis of OT. Our results clearly demonstrate the value of this approach; visual inspection of frequency spectra was sufficient to make a certain diagnosis in seven out of eight OT cases and strongly suggestive in the remaining patient. Of the numerous frequency spectra we examined from non-OT patients and controls, only one might have implied possible OT, and even this PD case was relatively easily distinguished as of alternative aetiology (Fig 3). Force platform recordings are very quick and straightforward to acquire; in some cases, our patients were only able to stand for around 20 seconds, but useful spectra were obtained. Force platform recordings were also found to show high coherence at the frequency of tremor with EMG traces from affected muscles. Overall, these data show a high correlation between EMG and posturography and confirm that OT may be diagnosed using short epochs of sway recorded from a force platform. To the authors' knowledge, this is the only condition for which force platforms can offer a disease-specific diagnosis. As a practical comment, visual identification of the tremor peaks was clearer when displaying frequency spectra in dB units.

A second goal for this study was the quantification of sway at differing frequencies in OT patients and controls, to assess objectively the reports of OT patients regarding their postural instability. OT patients were found to be significantly more unsteady than age matched controls across all frequencies, and to approach levels of sway exhibited by patients with cerebellar lesions at low frequencies. While the comparison was not perfect (some patients in both the OT and cerebellar groups required support to maintain quiet stance), such support would tend to minimise sway activity, so the finding of above average sway for the OT group is particularly striking. Body sway is massively concentrated at lower frequencies,

and it is sway increases at frequencies of less than 2-3 Hz that might represent the presence of genuine unsteadiness. Thus, sensations of unsteadiness in OT patients have, at least partially, an objective basis, although the mechanisms by which high frequency tremor might induce low frequency sway remain unclear. OT patients are not known to have somatosensory, vestibular or central, eg. cerebellar, defects. Speculatively, it is possible that the relevant somatosensory afferents from the lower limbs are being physiologically masked by high frequency muscular contractions. Such peripheral "bombardment" might interfere with the detection of sway signals by the proprioceptive system but further research is necessary to substantiate this point.

The final aim of this study was to investigate the timing patterns of muscle firings in the legs of OT patients. OT patients showed consistent but idiosyncratic patterns of EMG activity over the course of each period of quiet stance. These patterns did not typically support an explanation in terms of differing motor conduction times from a central oscillatory generator; ie there was no general tendency for distal muscles to fire after proximal ones.

In our OT patients, muscle activity patterns were reproduced during identical stance but with altered visual feedback (eyes open versus eyes closed). These results are broadly consistent with the findings of McAuley et al. [10], who reported patterns of muscle firing activity to be consistent within a given stance for a given patient, but to vary across stances (standing versus on "all fours") and between patients. Previous studies in OT have generally suggested that corresponding leg muscles on the two legs fire synchronously during stance, while agonist and antagonist muscles may fire synchronously or alternately [2,4,12]. Like McAuley et al [10], however, we found that a simple description of muscles firing either in synchrony or alternately did not accurately summarise the data.

In summary, OT can be efficiently diagnosed by visually inspecting frequency spectra derived from force platform signals, which show the high frequency postural tremor. These

patients exhibit increased low frequency body sway. The firing pattern of the tremor is consistent within each subject across differing conditions of visual feedback but differs between subjects.

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Legend to figure 1

Example EMG traces, alongside frequency spectra. All graphs are based on EMG data from the right tibialis anterior, obtained during the recording of sway with eyes open. The raw EMG data is for a typical one-second section of the complete recording; the y axis is calibrated to microvolts. For the frequency spectra, the entire obtained signal was used to calculate the spectral estimate; the y-axis is calibrated to microvolts/Hz. Force platform data from the same four patients is presented in figure 2.

Legend to figure 2

Example force platform recordings, alongside frequency spectra. All graphs are based on sagittal sway recorded with eyes open. The mean-removed sway path data is for a typical 10-second section of the complete recording; the y axis is calibrated to centre of mass deviation in cm. For the frequency spectra, the entire obtained signal was used to calculate the spectral estimate; the y-axis is shown in dB (a 20 dB increase represents a ten fold increase in absolute sway). EMG data from the same four patients is presented in figure 1.

Legend to figure 3

Frequency spectra of sagittal sway with eyes open for one patient with idiopathic Parkinson's disease (above) and one patient with OT (below). Note that while a peak exists at around 15 Hz in the upper graph, this appears to be a reduced-power harmonic of a lower frequency peak, a pattern that is not observed in patients with OT.

Legend to figure 4

Averaged sagittal sway for normal, OT and cerebellar-damaged groups with eyes open. Cerebellar patients were used for comparison because they are known to be unsteady and exhibit considerable body sway at low frequencies.

Legend to figure 5

Schematic representation of the pattern of leg muscle activation in one OT patient. All delays were calculated relative to sagittal sway. The upper part shows two cycles of sagittal sway, compared to coronal sway, for a sway frequency of 16 Hz. The lower part of the figure shows the main firing point for each of the 8 leg muscles recorded (± = S.D.).

Legend to figure 6

Correlation coefficients based on muscle firing patterns of OT patients. * denotes a correlation significant at $p < 0.05$, ** at $p < 0.01$. The top right of the table shows between-subject correlation coefficients based on eyes open data, while the bottom left section is based on eyes closed data. The central emboldened section shows eyes open/eyes closed correlations within each subject.

TABLE 1. Diagnostic success of EMG versus posturography data for seven previously diagnosed OT patients.

Patient	Frequency of tremor	Diagnosis of OT possible based on raw EMG*	Diagnosis of OT possible based on EMG frequency spectra*	Diagnosis of OT possible based on force platform frequency spectra**
BB	17 Hz	✔	✔	✔
EL	13 Hz	✔	✔	✔
MB	16 Hz	✔	✔	✔
WB	16 Hz	✔	✔	✔
TA	16 Hz	✔	✔	✔
AV	12 Hz	✘	✔	✔ ?
EK	16 Hz	✔	✔	✔

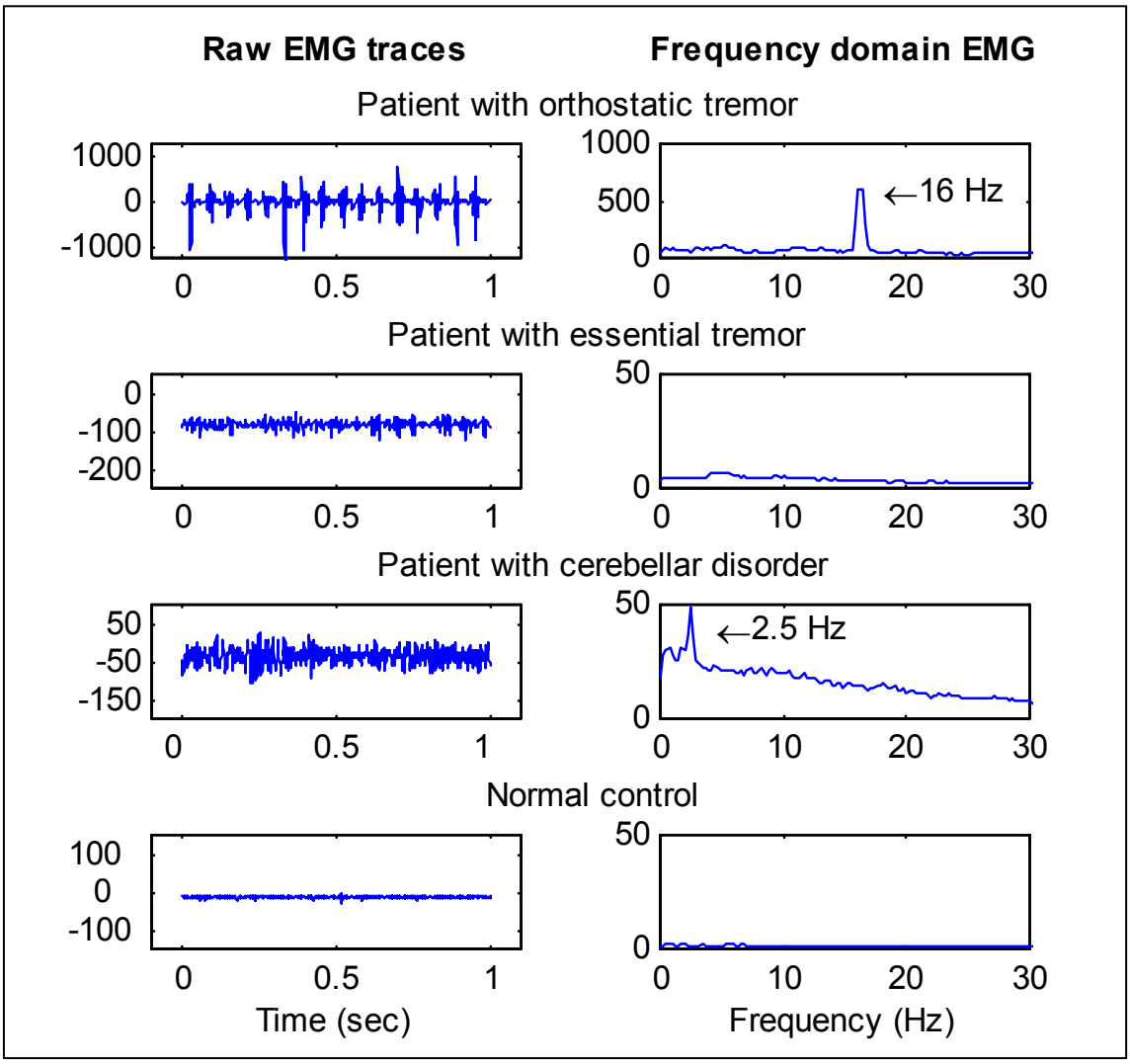
* EMG data were recorded from eight locations on each participant. For a successful diagnosis, clear OT characteristics were required in at least one muscle.

** Force platform data were obtained for both the sagittal and coronal plains. A successful diagnosis required a high frequency (12-18 Hz) peak to be evident in both planes of sway.

TABLE 2. Mean (± SD) sway (mm/Hz) for Normal, OT and Cerebellar groups in the sagittal plane with eyes open, in each of four frequency bands.

GROUP	Frequency Band			
	0.02 to 2 Hz	2 to 4 Hz	4 to 10 Hz	10 to 30 Hz
CEREBELLAR	3.162 ± 2.279	0.840 ± 1.581	0.079 ± 0.123	0.005 ± 0.005
	↕ NS	↕ NS	↕ NS	↕ Sig **
OT	1.358 ± 0.596	0.377 ± 0.188	0.101 ± 0.058	0.013 ± 0.007
	↕ Sig *	↕ Sig **	↕ Sig **	↕ Sig **
NORMAL	0.778 ± 0.140	0.071 ± 0.022	0.020 ± 0.0004	0.004 ± 0.002
	↕ Sig **	↕ Sig **	↕ Sig *	↕ NS
CEREBELLAR	3.162 ± 2.279	0.840 ± 1.581	0.079 ± 0.123	0.005 ± 0.005

Statistically significant differences (based on Kruskal-Wallis follow ups) are denoted in the space between each pair of groups; * = $p < 0.05$, ** = $p < 0.01$. N = 8 in each group.


Raw EMG traces
Frequency domain EMG
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0
0.5
1
1000
500
0
←16 Hz
0
10
20
30
Patient with essential tremor
0
-100
-200
0
0.5
1
50
0
0
10
20
30
Patient with cerebellar disorder
50
-50
-150
0
0.5
1
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10
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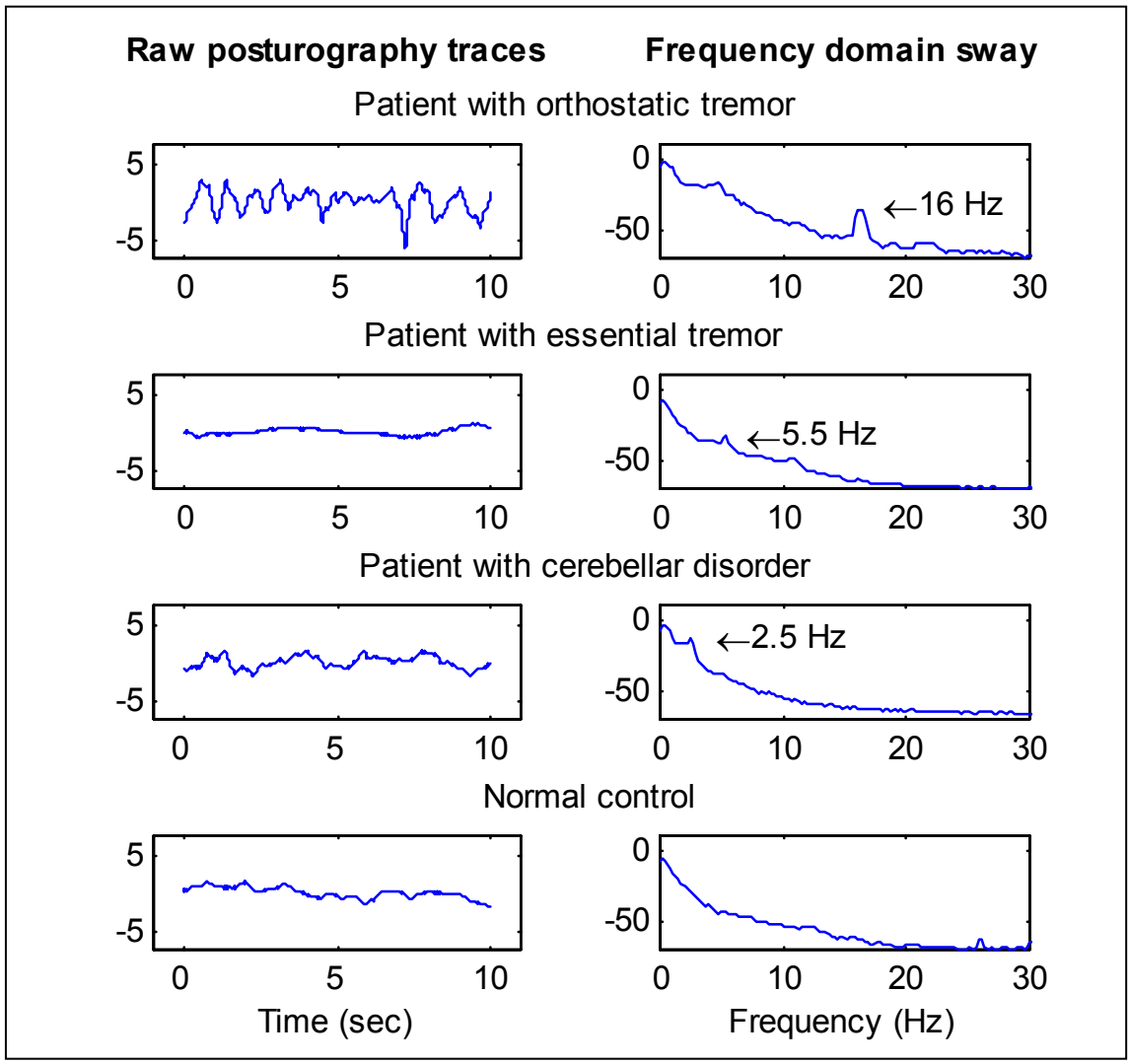
10
20
30
Frequency (Hz)


Raw posturography traces
Frequency domain sway
Patient with orthostatic tremor
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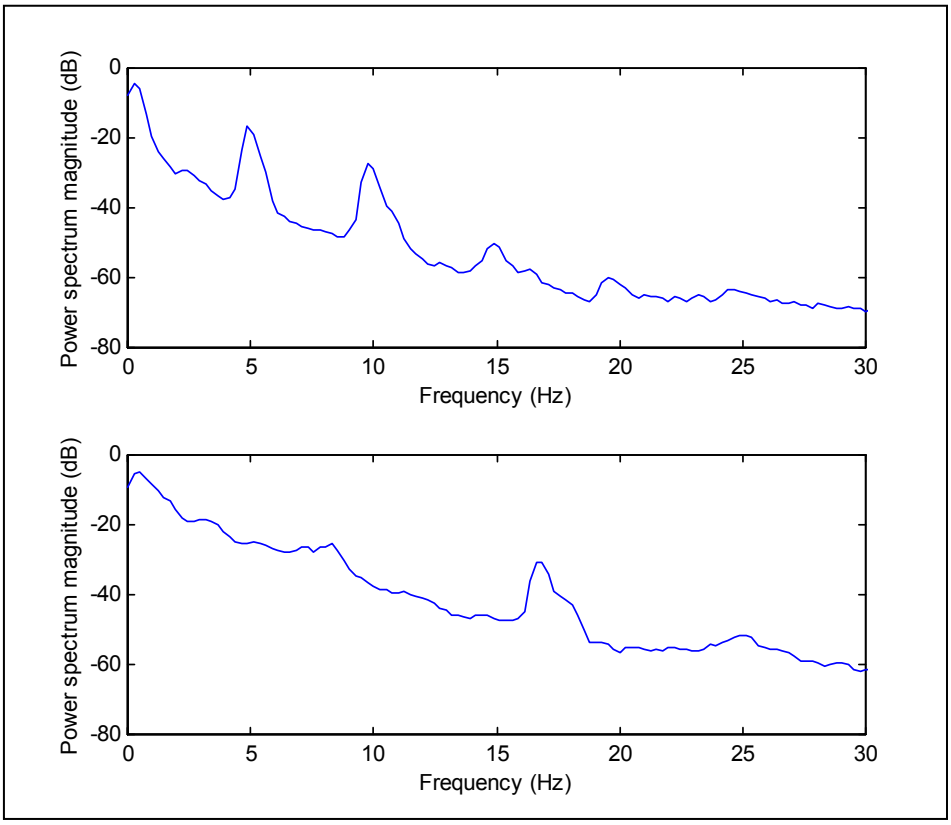
Patient with essential tremor
←5.5 Hz
Patient with cerebellar disorder
←2.5 Hz
Normal control
Time (sec)
Frequency (Hz)


Power spectrum magnitude (dB)
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-20
-40
-60
-80
0
5
10
15
20
25
30
Frequency (Hz)
Power spectrum magnitude (dB)
0
-20
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25
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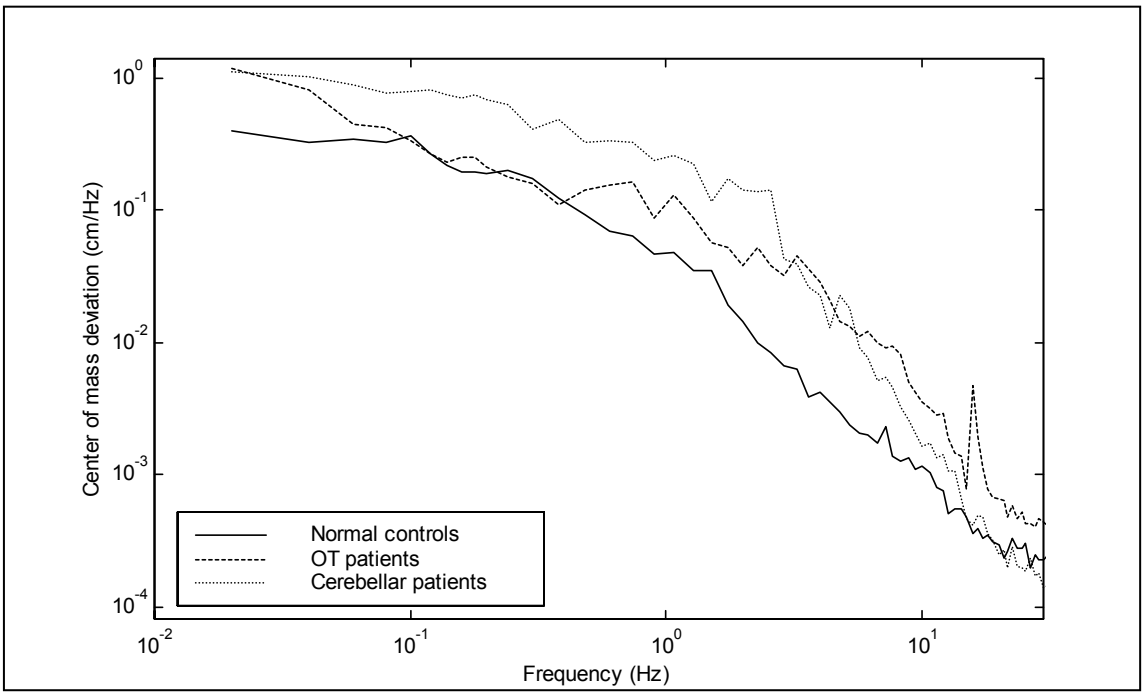
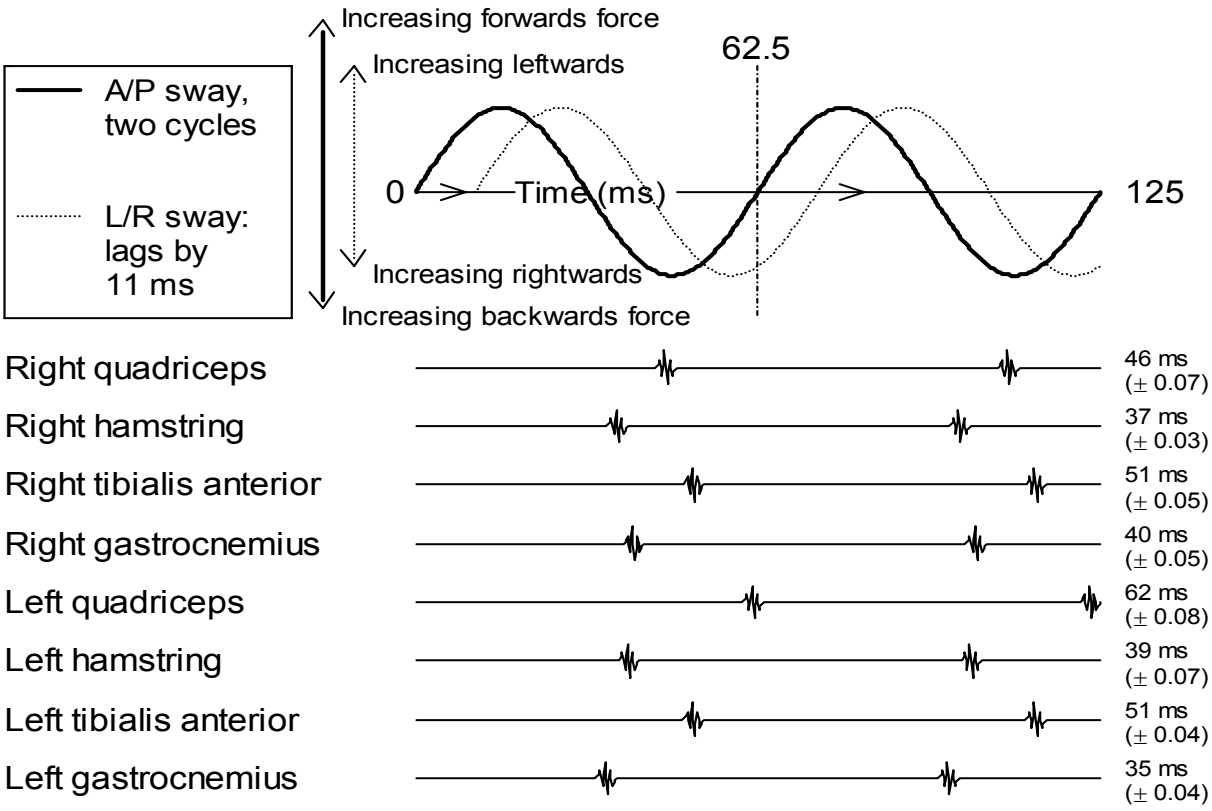
Frequency (Hz)


Center of mass deviation (cm/Hz)
Frequency (Hz)
Normal controls
OT patients
Cerebellar patients


A/P sway, two cycles
L/R sway: lags by 11 ms
Increasing forwards force
Increasing leftwards
62.5
0
Time (ms)
125
Increasing rightwards
Increasing backwards force
Right quadriceps
46 ms (± 0.07)
Right hamstring
37 ms (± 0.03)
Right tibialis anterior
51 ms (± 0.05)
Right gastrocnemius
40 ms (± 0.05)
Left quadriceps
62 ms (± 0.08)
Left hamstring
39 ms (± 0.07)
Left tibialis anterior
51 ms (± 0.04)
Left gastrocnemius
35 ms (± 0.04)

Patient	BB	TA	EL	WB	EK	AV	MB	
BB	**1.00****	0.11	0.82**	0.31	0.02	0.61	0.96**	Between subjects correlation: eyes open
TA	0.00	**1.00****	0.46	0.36	-0.03	-0.02	0.23	
EL	0.77*	0.44	**1.00****	0.23	0.12	0.35	0.86**	
WB	0.32	0.53	0.38	**0.97****	0.27	0.77*	0.43	
EK	-0.59	0.07	-0.25	0.20	**0.67****	0.46	0.03	Within subjects correlation: eyes open condition correlated with eyes closed
AV	0.69*	-0.10	0.44	0.66	0.03	**0.99****	0.67*	
MB	0.91**	0.23	0.88**	0.53	-0.37	0.70*	**0.99****	
	Between subjects correlation: eyes closed							