J. Physiol. (1984), **348**, *pp.* 559–572
With 6 *text-figures*
Printed in Great Britain

PROPRIOCEPTORS AND NORMAL TREMOR

By J. A. BURNE*, O. C. J. LIPPOLD and M. PRYOR
From the Department of Physiology, University College London WC1E 6BT

(*Received 11 May 1983*)

SUMMARY

1. The tremor of the hand, rotating about the wrist joint, was measured using an accelerometer, and groups of muscle action potentials were simultaneously recorded from the wrist extensor muscles using surface electrodes. The accelerometer signal and the rectified, demodulated electromyogram were submitted to Fourier analysis in order to quantify the tremor in terms of its frequency components and the amplitudes of those components.

2. The amplitudes of the 8–12 Hz peak in the frequency spectrum obtained from muscle electrical activity were compared (a) when the hand was held raised against gravity (i.e. the contraction was isotonic) with (b) when it was held raised, with the same force and in the same position against a rigid bar (i.e. the contraction was isometric).

3. In the isotonic condition (a) a prominent 8–12 Hz peak was observed in the spectrum. In the isometric condition (b) the peak was small or absent.

4. The conclusion is drawn that the grouping (synchronization) of motor unit action potentials underlying tremor cannot be due to any process in the central nervous system generating them and they depend on cyclic alterations in muscle length activating proprioceptors.

INTRODUCTION

During voluntary contractions, constant force is achieved through asynchronous firing of motor units. Any tendency towards synchronization of motor unit discharge will give, superimposed on the mean tension, an oscillation in tension the amplitude of which will be a function of the proportion of motor units firing in this way. The tremor that results can be recorded as an oscillation in limb position using a suitable mechanical transducer or as a series of synchronized discharges of motor units from the surface electromyogram (Elble & Randall, 1976; Gottlieb & Lippold, 1983).

Tremor recorded as an oscillation in finger or hand position commonly shows a dominant frequency component in the 8–12 Hz band. Some authors (e.g. Lance, 1970) have postulated that this form of tremor results from active synchronizing influences originating within the central nervous system. Taylor (1962) has proposed, on the basis of experimental observations, that tremor is due to 'chance' synchronization of motor units and more recently statistical analysis of parallel spike trains

* Present address: Cumberland College of Health Sciences, Lidcombe, N.S.W. 2141, Australia.

(Christakos & Lal, 1979*a*, *b*, 1980; Milligan & Lal, 1982) showed theoretically that the spikes from different trains tend by chance to produce brief periods of synchronous activity at the predominant frequency occurring in the individual trains. It was, on this basis, claimed that the 8–12 Hz band of finger tremor could be explained in purely statistical terms.

Synchronization of motor unit discharges could, however, reflect the presence of a synchronized input of peripheral origin. Such an input will result if there is oscillation in the reflex loop involving the response of limb proprioceptors to tremor-generated movements (Halliday & Redfearn, 1956; Lippold, 1970, 1973). Support for such a proposal is derived from the observations that tremor frequency is altered predictably by treatments which alter reflex delay, such as heating and cooling (Lippold, 1970; Furness, 1977); that tremor amplitude is reduced by short-term ischaemic block known to involve only the afferent limb of the reflex pathway (Halliday & Redfearn, 1954; Lippold, 1973); and that step-function mechanical perturbations of limb position result in phase-locked, damped trains of tremor oscillations of the limb (Lippold, 1970).

The question of whether the synchronization (grouping) of motor unit firing underlying tremor is primarily of central origin, or is due to the input from peripheral limb proprioceptors having an intermittent nature, can easily be settled. The grouping of motor units can be seen in the electrical record from wrist extensor muscles when the hand is held raised against gravity. If the hand is then raised to the same position with the same mean force against a rigid stop, there is little or no synchronization apparent in the muscle action potential record. Therefore the synchronization cannot be of purely central origin. These experiments are described in this paper.

We also describe experiments showing that the 8–12 Hz tremor of the wrist is the result of 8–12 Hz modulation of motor unit activity. When the arterial supply to the arm is briefly occluded, the 8–12 Hz synchronization in the electrical record obtained from the wrist extensor muscles is eliminated *pari passu* with the 8–12 Hz tremor peak, although there is no diminution in motor power.

METHODS

Subjects

Subjects were twenty-nine unselected male and female volunteers in the age range 19–59 years. Informed consent was given by all subjects and the protocol was approved by the local ethical committee.

Recording arrangement

Subjects were seated comfortably and the left elbow and forearm supported at a natural height, with the arm held in a horizontal position by a closely fitting plaster mould which was rigidly mounted on to a small recording stage. The forearm was further stabilized at a point immediately proximal to the wrist joint by the pressure of a metal bar also mounted on the recording stage. The fingers and hand were splinted with a lightweight aluminium alloy bar and bound with plastic adhesive tape, taking care not to occlude the circulation. The arrangement permitted free wrist flexion and extension movements while eliminating, or minimizing, movements about other joints in the limb.

Electromyography

The electromyogram of the wrist extensor muscles was recorded using silver disk skin electrodes (0·9 cm diameter) which were placed over the body of the muscle, and secured with plastic adhesive. The positioning of the electrodes was determined by careful trial to maximize the electrical activity for a given extension of the wrist. The signal was filtered (3 dB points at 80 Hz and 10 kHz, full-wave rectified and smoothed to produce a demodulated signal using a third-order Butterworth filter set to remove frequencies above 18 Hz (Gottlieb & Lippold, 1983; Elble & Randall, 1976).

Accelerometry

In some experiments hand tremor (in the flexion–extension plane of the hand) was also recorded with an accelerometer (Brüel & Kjaer, type 4367) which was attached to a plastic ring and placed over the tip of one of the fingers of the splinted hand. The output of the accelerometer was subjected to spectral analysis.

Analysis

Frequency analysis of the rectified and demodulated signal was carried out in real time using the Hewlett–Packard 3582A spectrum analyser, remotely programmed with a type 9528A desk-top computer and automatically plotted on a type 7225 graphics plotter. The frequency span was 0–25 Hz, which gave a time record length ($N\Delta t$) of 10 s, and a calculated point spacing (Δf) of 0·1 Hz. A Hann pass-band shape was used, to minimize leakage, giving 0·15 Hz equivalent noise band width. Since the sampling frequency was 102·4 kHz (i.e. Nyquist frequency = 51·2 kHz) alias contamination did not occur within the specified frequency range. Four separate, consecutive 10 s power spectra were averaged to give 90% confidence limits between +4·7 and −2·9 dB for each spectral point.

The smoothed spectra shown in Fig. 6 were obtained by the method of thirds. For each spectral power point the computer summed its value with that of the adjacent two points and calculated the mean. This process was repeated thirty-two times. Before display, the square root of each smoothed point was extracted to produce the amplitude spectrum.

Procedure 1: comparison of tremor under isometric and isotonic conditions

Samples of tremor (40 s duration) were taken for analysis during periods of maintained wrist extension, the hand having been raised to a reference mark through an angle of about 30 deg from the recording platform. A total of thirty experiments were performed on seventeen subjects: (*a*) with hand position maintained by voluntary contraction of the extensor muscles alone, and (*b*) with the hand in a similar position and contracting isometrically against an appropriately fixed metal bar (see Fig. 1).

Force equalization

The amount of tremor displayed during muscular contraction varies directly with the force of that contraction in a given subject (Sutton & Sykes, 1967). It is therefore necessary, when comparing the amplitude of 8–12 Hz tremor under different conditions, to ensure that the contraction strength remains constant. The integrated electromyogram from the wrist extensor muscles was displayed on a suitably damped moving-coil meter and on an oscilloscope so that it could be monitored by both subject and experimenter throughout the recording period. Since the integrated electromyogram is linearly related to force (Lippold, 1952), this enabled the level of muscle contraction to be held constant during the recording of each sample and between samples (a) and (b).

In certain experiments the force of contraction was equalized during (a) isotonic and (b) isometric conditions using a small weight. When the conditions were required to be isotonic a 20 g weight was taped to the splint. For isometric conditions, the subject was instructed to press upwards with a force of 20 g against the bar, to which was attached a strain gauge. Care was taken to ensure that the position of the fingers, hand, wrist joint, forearm and upper arm were identical under the two conditions (a) and (b).

Thus, in both these procedures, the recording mode differed only in that during isotonic contraction (a) the hand was free to exhibit tremor movements (under the influence of gravity) whilst in isometric contraction (b) it was not.

In some experiments additional measures were taken to ensure isometric recording conditions.

These were aimed principally at improving immobilization of the hand while it was being contracted against the metal bar. In a few cases the fingers, or part of the hand, were taped to the bar. In a few others the splint was removed to allow the hand to be embedded in 'Plasticine' before being sandwiched between two sheets of Perspex.

Procedure 2: the effect of arterial occlusion on tremor

For the production of ischaemia, a sphygmomanometer cuff was rapidly inflated on the upper arm and maintained at a pressure of 200 mmHg for the required time. In these experiments hand tremor was monitored by the accelerometer, periodic samples being subjected to on-line frequency analysis. In four experiments the accelerometer output and smoothed electromyogram were both recorded on magnetic tape for later analysis. In this way it was possible to obtain a parallel frequency analysis of both records which was updated at 10 s intervals.

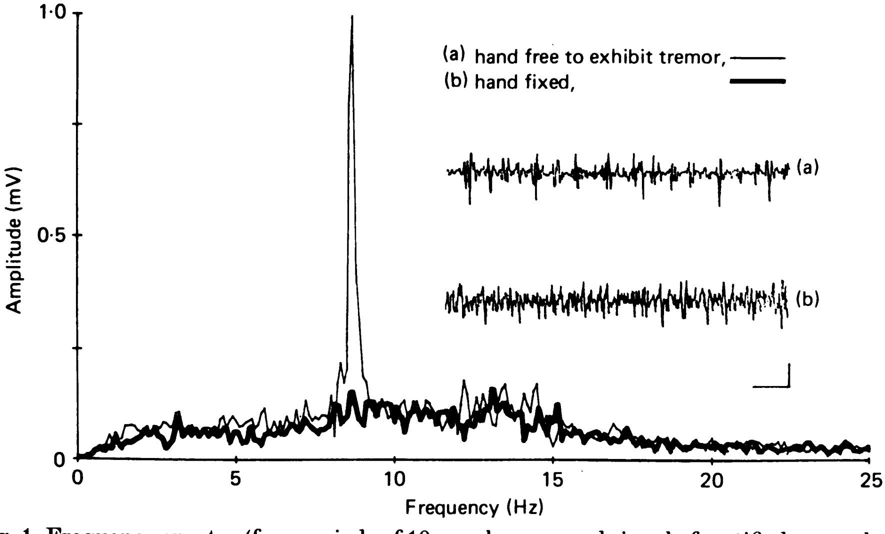

Fig. 1. Frequency spectra (four periods of 10 s each, averaged signal of rectified, smoothed electromyogram from wrist extensors (a) with wrist raised 30° and held up to a mark, but free to move (b) with wrist fixed in the same mean position as (a), but exerting upward force equal to that during condition (a). Force of muscle contraction was that required to raise the hand, plus 20 g. The integrated electromyogram was kept the same, by the subject, for conditions (a) and (b). (In other experiments a 20 g weight was strapped to the hand during condition (a).) Hand, wrist, arm, forearm and shoulder in the same position during (a) and (b). Rotation permitted only at wrist joint. Inset shows the raw electromyogram record obtained under conditions (a) and (b), as plotted after analog–digital conversion with a digital plotter. Calibrations = 1 mV, 100 ms.

The effect of 2 min ischaemia was investigated (a) during maintained wrist extension (seventeen subjects), (b) during maintained extension with weights of 100 or 300 g added to the hand (thirteen subjects), and (c) while the hand was hanging vertically and in the absence of detectable electrical activity in the wrist extensors as described by Birmingham, Williams, Wilson & Wright (1977) (four subjects).

Calibration

Calibration of recordings was carried out in the usual way after each experiment. For accelerometry the calibration curves supplied with the transducer were employed. It will be noted that all spectral components are given as an amplitude in mV. This is so because the spectral values are expressed as the square root of their power when they are plotted (for reasons given in Gottlieb & Lippold, 1983).

The amplitude scales are referred to mV at the electrodes and were obtained by using a 3 Hz sine wave of 1 mV peak-to-peak amplitude applied to the input plugs (with the electrodes disconnected and time constant set to 0·2 s), the source impedance being 4 MΩ. Gains were adjusted to give a full scale deflexion peak in the spectrum (= 40 mV/spectral point) with the 1 mV calibrating signal. The accelerometer gave 31·6 mV input to the analyser for a linear acceleration of 1 m/s^2 and had 3 dB cut-off points in the charge amplifier at 0·1 kHz and 0·2 Hz. Gains were adjusted to give full scale deflexion (= 40 mV/spectral point) for an acceleration of 5 m/s^2.

TABLE 1. Comparison of peak amplitudes in the 8–12 Hz range of the electromyogram spectrum when the hand was free (column a) or fixed (column b)

Subject no.	Expt. no.	Peak amplitude (a)	Peak amplitude (b)	Percentage change
1	1	62	10	84
	2	35	20	43
2	3	41	2	95
	4	48	0	100
	5	46	0	100
3	6	46	0	100
4	7	65	11	83
5	8	35	9	74
	9	54	6	89
6	10	55	7	87
	11	32	10	69
7	12	56	8	82
8	13	46	0	100
	14	42	10	76
9	15	67	11	84
10	16	42	25	40
11	17	51	23	55
12	18	80	9	88
	19	50	16	63
13	20	53	0	100
14	21	61	0	100
15	22	38	0	100
16	23	94	23	76
	24	55	3	95
	25	112	3	97
	26	46	2	96
	27	102	12	88
	28	88	8	91
	29	52	15	71
17	30	62	13	79

Peak amplitude was measured as the ratio between the amplitude of activity in the largest single bin and the mean amplitude of the highest values for the base line in the range up to 1 Hz below and from 1 Hz above the peak itself. Force in (a) and (b) was always 20 g plus that required to maintain the hand raised against gravity. (Total weight of the hand as measured by volume of water displaced was 200–400 g.)

RESULTS

Normal hand tremor

Frequency analysis of the rectified, demodulated electromyogram from wrist extensors during the presence of hand tremor gave a characteristic frequency spectrum containing a pronounced peak at about 9 Hz. This peak was 2–5 times the amplitude of the background spectrum (Fig. 1 condition (a) and Table 1).

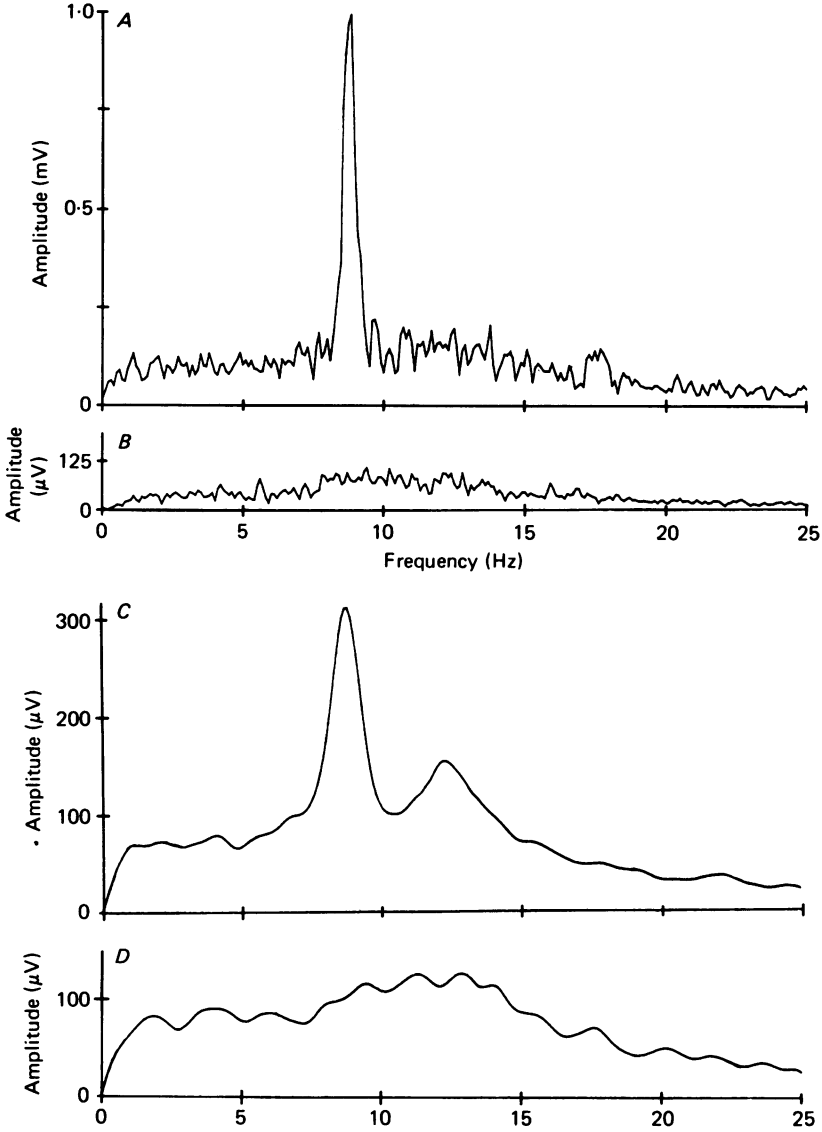

Fig. 2. Spectra from accelerometer; hand splinted. *A*, control; circulation intact. *B*, 40 s averaged spectrum after 160 s with cuff on at 200 mmHg. *C* and *D*, simultaneous spectra from smoothed electromyogram. (For *C* and *D* spectra were smoothed digitally.) Peak at 8·2 Hz has been abolished by the brief period of ischaemia, in both accelerometer and electromyogram spectra. Recovery was complete by 2 min following release of cuff.

'Tremor' with hand fixed

Since it is possible to record tremor electrically, from bursts of action potentials arising in the muscle, a comparison can be made between tremor when the hand is free to move or is firmly fixed. Fig. 1 shows two spectra from the wrist extensor muscles taken (a) with the hand held horizontal but free to tremble and (b) with the hand fixed in the same position and exerting the same upward force as in (a). The upward force in this experiment was 20 g. The total force exerted by the muscle was, of course, more than this, being the weight of the hand plus 20 g.

Table 1 shows the heights of the 9 Hz peaks in the free and fixed condition as found in thirty experiments on seventeen subjects.

TABLE 2. A, comparison of tremor amplitudes (amp.) and frequencies (freq.) before and after application of arterial cuff when three weights are lifted. Peak acceleration is again expressed as a multiple of values recorded at adjacent frequencies. B, the effect of arterial cuffing on tremor amplitudes and frequencies as recorded by accelerometer and smoothed electromyogram

A

	Before cuffing						After cuffing					
	0 g		100 g		300 g		0 g		100 g		300 g	
Subject no.	Amp.	Freq.	Amp.	Freq.	Amp.	Freq.	Amp.	Freq.	Amp.	Freq.	Amp.	Freq.
1	14·0	8·2	9·1	7·2	8·1	6·2	4·5	7·9	5·0	7·2	2·2	6·2
2	12·4	9·5	5·8	8·0	2·2	6·8	2·8	9·5	4·6	8·0	1·3	6·5
3	45·0	8·8	12·0	7·6	5·0	6·5	14·0	8·5	12·0	7·6	4·0	6·2
4	13·0	7·6	9·6	6·8	9·6	5·8	12·8	7·0	6·5	6·3	11·8	5·5
5	18·0	8·6	18·0	7·7	9·0	6·9	10·0	7·6	7·0	7·3	3·5	6·2
6	6·7	8·5	7·9	7·5	6·8	6·4	3·0	7·5	4·9	6·7	2·9	5·6
7	8·8	9·0	3·7	7·5	6·4	6·2	1·2	8·5	1·2	7·5	1·6	5·7
8	6·5	8·9	4·0	7·9	2·0	6·0	3·0	8·3	1·8	7·4	1·2	6·0
9	22·0	8·5	5·2	7·2	2·5	5·8	1·5	8·2	1·0	6·8	1·0	5·7
10	18·0	9·1	7·6	7·2	16·4	5·1	4·6	7·6	4·4	6·5	10·0	4·8
11	11·5	10·0	9·0	8·2	2·2	6·8	5·2	8·3	4·0	7·5	2·2	6·2
12	7·8	8·8	6·0	7·7	3·1	6·3	4·8	8·5	4·6	7·7	2·4	6·1
13	23·0	8·5	19·0	7·3	19·0	5·7	9·0	8·1	13·0	7·0	7·0	5·5
Mean	20·5	8·7	9·1	7·6	7·1	6·2	6·2	8·1	5·0	7·2	3·2	5·9

B

	Accelerometer				Smoothed e.m.g.			
	Amp.		Freq.		Amp.		Freq.	
Cuffing	Before	After	Before	After	Before	After	Before	After
14	30	5	8·2	8·0	9	0	8·2	—
15	40	10	8·0	7·0	4	1·5	8·0	7·0
16	40	4	9·0	9·0	8·5	0	9·0	—
17	32	10	8·5	8·0	14	0	8·5	—

The results show that the 8–12 Hz peak can be made to disappear without altering the level of activity in other frequency bands when the hand is immobilized in a firmly fixed clamp.

In some experiments the peak was reduced but was not completely absent in the clamped state. The reason for this was often found to be that fixation still allowed a small degree of movement to take place (either as a slight bending of finger joints or as a wrist movement); when fixation was improved in these cases, the amplitude of the 8–12 Hz peak was further decreased.

Arterial occlusion and normal hand tremor

Spectral analysis of accelerometer recordings of hand tremor during maintained wrist extension exhibited a pronounced peak in the 8–12 Hz band in all seventeen subjects tested. Periods of arterial cuffing for up to 160 s reduced the amplitudes of these peaks by between 38 and 90 % in sixteen subjects (Fig. 2 and Table 2). The peak showed a rapid and progressive decline over the first 10 s which was followed by a further more gradual decrease over the next 100 s. It is likely that a longer period of application of the arterial cuff would have further reduced the peak amplitudes.

The effect of cuffing on tremor has been attributed to the high susceptibility of the proprioceptive afferent terminals to ischaemia (Lippold, 1970, 1973), interrupting the reflex loop. In four further experiments the close correlation between tremor

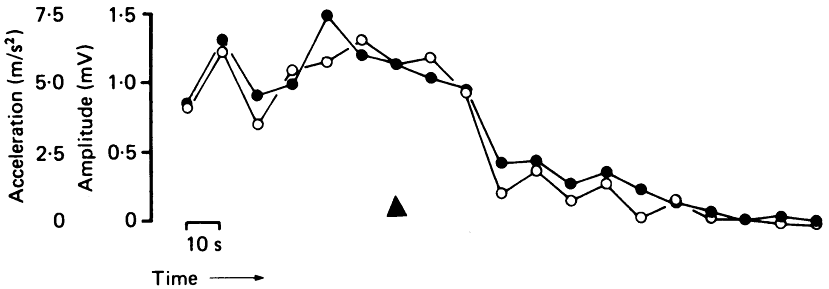

Fig. 3. Amplitude of spectral peaks at 8·5–7·5 Hz plotted against time. Curve with filled symbols obtained from Fourier analysis of accelerometer signal; curve with open symbols obtained from Fourier analysis of smooth, rectified electromyogram, at same times. Cuff inflated to 200 mmHg on upper arm at large arrow. The correspondence between the two curves indicates that the mechanical tremor and its concomitant electromyogram are closely related. The electromyogram peak falls to zero, indicating that periodicity in the neural input has been abolished by the arterial cuff.

amplitude and the synchronized 8–12 Hz electromyographic activity in the tremor-producing muscles was demonstrated. Concurrent spectral analysis of the smoothed electromyogram and accelerometer recordings of hand tremor showed close correlation between amplitudes of the tremor and electromyogram peaks both before and during cuffing (Figs. 3 and 4). The 8–12 Hz electromyogram peak was completely abolished by less than 2 min of cuffing in three subjects and reduced by 63 % in the remaining subject.

Fig. 3 shows the effect of 160 s duration of arterial cuffing on hand tremor. The peak amplitudes of acceleration (measured with the transducer) and of neural input (estimated by smoothing the rectified electromyogram) are plotted against time. After control measurements, the arterial cuff was inflated (at the arrow). This procedure resulted in the amplitudes of the two separately derived peaks falling in a similar manner with time. Note that the effect of the cuff was confined to the 8–12 Hz peak, confirming that the mean level of motor activity was not reduced.

In Fig. 4 the amplitudes of the accelerometer peaks from four subjects are plotted against the corresponding electromyogram-derived peak amplitudes. The points may be seen to approximate a straight line ($r = +0{\cdot}92$).

Control observations showed that maximal voluntary force was not affected by a period of ischaemia lasting for 160 s.

Hand tremor in the absence of muscle activity

In four subjects tremor was recorded using the accelerometer while the hand hung freely from the wrist with the arm vertically downwards, there being no detectable activity in the electromyogram from wrist extensors. The spectral analysis of the accelerometer output yielded a peak in the 8–12 Hz band, though its amplitude was between 1 and 10% of that obtainable during muscle activity. This confirms studies by Lakie, Walsh & Wright (1983) and Walsh & Wright (1982).

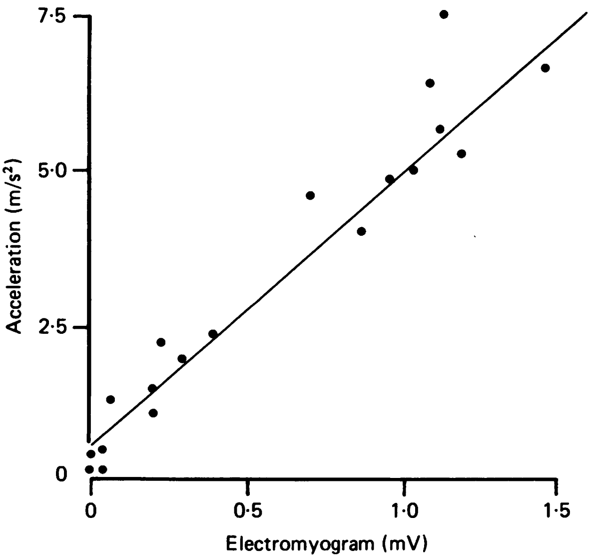

Fig. 4. Plot of amplitudes of accelerometer spectral peaks at 8–12 Hz and corresponding electromyogram spectral peaks. Product moment correlation coefficient, $r = +0{\cdot}92$. There is a positive intercept on the Y-axis.

Control observations

Though mechanical resonance of the wrist alone may account for only a small percentage of tremor amplitude, there remains the possibility that this is detected and amplified by the reflex arc. We have therefore to confirm that cuffing does not alter this parameter, particularly in view of reports that the mechanical oscillation is driven by the pulse (Brumlik, 1962). Fig. 5 contains accelerometer records of tremor recorded while the hand was hanging downwards in the absence of muscle activity. The tremor appears as a series of damped oscillations which appear to be driven by the cardiac action. It can be seen that cuffing is without effect on this form of tremor, though it greatly alters that occurring during extensor activity.

Mechanical factors in tremor of the hand

Tremor must arise from an application of force acting across a limb joint to give a displacement; if the limb is underdamped, this displacement will be in the form of a series of oscillations whose frequency will depend mainly upon the viscoelastic-mass properties of the limb. If the input force has a periodicity at about the natural frequency of the inertial system of the limb, driving will occur and tremor will build up. If the input force is aperiodic, tremor will still occur at the natural frequency of the limb, although in general its amplitude will be smaller. When the input force is periodic, but at a frequency different from the natural frequency of the limb, oscillation at two distinct frequencies may occur, one mechanically determined, the other being the input frequency. In the case where the natural frequency of the limb is lower than that of the input force, the vibration of the limb is restricted to the former frequency (and/or lower ones).

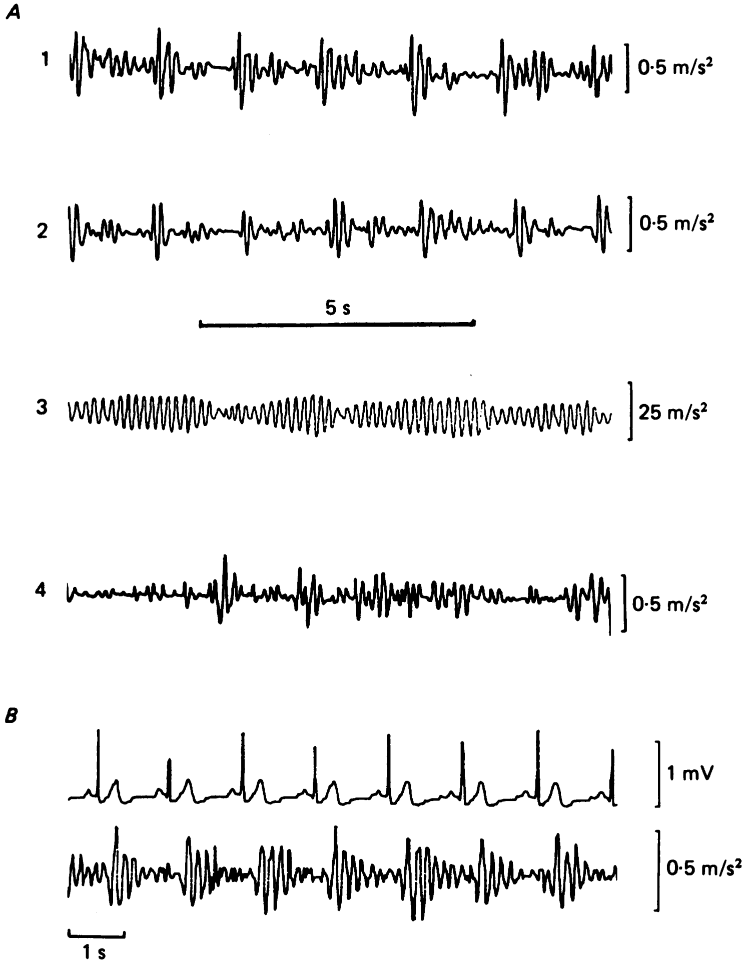

Fig. 5. *A* shows a series of accelerometer recordings of tremor while the hand is hanging freely. Record 1 is before, and 2 during cuffing. Records 3 and 4 were recorded in the usual manner while the hand was raised; 3 was before and 4 during arterial cuffing. Note that the gain in record 3 is 1/50 that of the other traces. *B*, top line, electrocardiogram from lead I and bottom line, the simultaneous tremor record obtained with the hand hanging freely, no cuff on. In all recordings apart from 3 and 4, the absence of muscle contraction was checked using electromyogram recording from the flexors and extensors.

It follows that the finger, having a viscoelastic-mass-determined frequency of between 20 and 30 Hz (Stiles & Randall, 1967) would exhibit two tremor peaks if the input force was periodic at a substantially lower frequency than this. Experimentally, it is found that the finger does have two major tremor peaks, one between 20 and 30 Hz while the other lies between 8 and 12 Hz (Halliday & Redfearn, 1954).

The viscoelastic-mass-determined resonant frequency of the hand is usually between 7 and 10 Hz, thus falling within the same band as the tremor due to reflex oscillation. Small amounts of tremor remaining after abolition of synchronization in the electromyogram by cuffing can therefore be attributed to mechanical resonance.

The effect of added mass

The taping of 100 or 300 g weights to the tip of the outstretched hand reduced tremor frequency by 0·8–1·9 Hz (mean 1·1 Hz) and 2·0–4·0 Hz (mean 2·5 Hz) respectively in thirteen subjects. Added mass also reduced the amplitude of the spectral peak, mean values falling to 45 % of control values after 100 g and 35 % after 300 g.

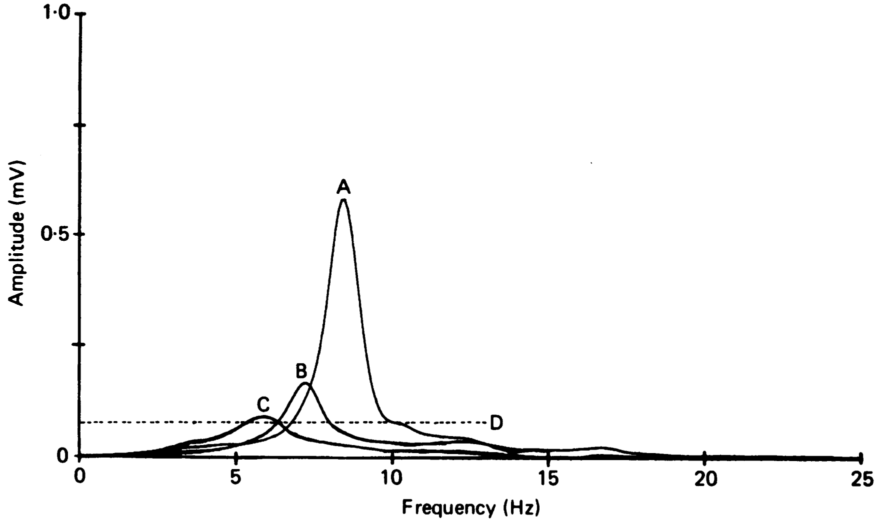

Fig. 6. Smoothed spectra from accelerometer on the hand. A, no weight attached. B, 100 g and C, 300 g. Added weights lower peak frequency and also peak amplitude. After 160 s application of an arterial cuff, all three peaks were reduced to a small amplitude, below that shown as dotted line D, peak A being 1·5 mV and peaks B and C 1·0 mV.

These values were further reduced by 2 min of cuffing, the large peak from the unloaded hand at 8·7 Hz being proportionately most affected (Fig. 6). Tremor frequency was little affected by cuffing, being only slightly reduced (mean frequency shifts were 0·6, 0·4 and 0·3 Hz for the 0, 100 and 300 g peaks respectively) (Fig. 6, Table 2).

Comparison of the amplitudes of the three peaks in Fig. 6 before and after cuffing shows that the size of the neural component in each peak is frequency dependent, declining rapidly at frequencies below 8 Hz. In contrast, the mechanical component which remains after cuffing is relatively stable over the range of weights used, the small decrease seen being a measure of mechanical damping effects.

Thus wrist tremor frequency is largely determined by the viscoelastic-mass properties of the limb and may readily be modified by a change in these properties, though its amplitude is large only when the viscoelastic-mass properties permit oscillation in the 8–12 Hz band. At this frequency the periodic reflex and mechanical resonant input are matched and the resonance which results gives rise to the large-amplitude tremor.

DISCUSSION

The appearance of synchronized activity at 8–12 Hz in the electromyogram of the wrist extensor muscles is dependent on tremor-associated limb oscillations, as shown by the fixating experiments. Further, we can deduce from the cuffing experiments that this synchronization produces normal wrist tremor. We conclude that the tremor arises from oscillation of activity in the proprioceptive reflex loop.

The dependence of tremor on the normal operation of the stretch reflex loop invalidates theories which attribute tremor to purely central mechanisms. Prominent amongst them are those of Marshall & Walsh (1956) who suggested that the muscle acts as a low-pass filter, the tremor being a result of firing of unfused motor units at frequencies between 8 and 12 Hz. Elble & Randall (1976) and Lance (1970) have suggested (though no evidence is cited) that Renshaw inhibition produces repeated periods of synchronization at the tremor frequency. The foregoing theories, as well as those attributing tremor to the statistical properties of motor unit firing, require tremor to be independent of the operation of the afferent limb of the reflex pathway, and hence the tremor would not have been affected by the fixating or cuffing treatments used here, if the theories were true.

The practical difficulties of achieving truly isometric conditions within a muscle when it contracts would make it unlikely that the 8–12 Hz peak could be abolished in all subjects. Even assuming complete immobilization of the limb, the possibility remains that internal shortening of the muscle still occurs, even though externally the contraction is isometric. There was considerable variation in the effectiveness of the different immobilization techniques used when applied to different subjects; it is conceivable that in subjects displaying large-amplitude tremor, where reflex gain is presumably high, internal muscle shortening produces sufficient reflex activity to generate tremor in the absence of external movement.

We may now address the question of the relative contribution of mechanical and neural factors in determining tremor characteristics. Since the peak at 8–12 Hz in the hand tremor is greatly reduced or abolished by application of an arterial cuff, it appears that the major part of the force input required to sustain this vibration is neural in origin. Furthermore, it must be the periodic or reflex component of this neural input that is important, because the neural activity in the remaining frequency bands is not altered by ischaemia. Comparison of the tremor spectral peaks obtained using an accelerometer with those obtained using analysis of the electromyogram, shows that both decline in amplitude in the same fashion when the cuff is applied. This strengthens the conclusions that tremor of the hand is mainly neural in origin, although the facts that the freely hanging hand shows some tremor in the absence of any neural input and that there is a positive intercept on the line relating peak amplitudes obtained by the two methods, indicate that there is still some forcing input to the system in the confirmed absence of the periodic neural one.

A pointer to the origin of the mechanical forcing input is apparent in Fig. 5 which shows that, in the absence of any neural input, hand tremor displays regular damped trains of up to ten waves of oscillation each, at between 8 and 12 Hz, presumably linked with each pulse beat. Brumlik (1962) by computer averaging, has shown that this hand tremor is causally related to the heartbeat. Part of the residual tremor, not originating in periodic neural inputs, may also arise as forcing by aperiodic neural inputs. However, the amplitude of tremor originating in this way must be relatively small and cannot exceed about 10% of the total peak tremor amplitude in our experiments, as can be seen from Fig. 4.

Our results show that peripheral factors such as inertia of a limb and the viscoelastic properties of its muscles, tendons and joints directly determine the amplitude and frequency of normal tremor. They also show that the major part of wrist tremor is primarily generated by the cyclic operation of stretch receptors (and/or joint receptors) in the wrist musculature.

Much of the controversy with respect to the origin of normal tremor has arisen from the fact that the measurement of tremor force under isometric conditions often reveals very little or no peak activity at 8–12 Hz. If the recording conditions are such as to prevent activation of muscle proprioceptors, this is the predicted result. It is also worth pointing out that tremors in muscles other than those we have studied may have different origins, in spite of their frequency spectra being similar.

O. C. J. Lippold is indebted to the Wellcome Trust for a grant in support of this work. J. A. Burne was on leave from Cumberland College of Health Sciences, N.S.W. 2141, Australia. We are most grateful to E. G. Walsh, B. Lynn and Sue Gottlieb, who read the manuscript and made many helpful suggestions.

REFERENCES

Birmingham, A. T., Williams, E. J., Wilson, C. G. & Wright, P. W. (1977). Finger tremor in normal subjects. *J. Physiol.* **276**, 20–21*P*.

Brumlik, J. (1962). On the nature of normal tremor. *Neurology* **12**, 159–179.

Christakos, C. N. & Lal, S. (1979*a*). Force predictions relating to tremor and other consequences of a 'distributed' model of skeletal muscle. *J. biomed. Eng.* **1**, 175–176.

Christakos, C. N. & Lal, S. (1979*b*). Asynchronous motor unit activities and tremor. *J. Physiol.* **203**, 42–43*P*.

Christakos, C. N. & Lal, S. (1980). Lumped and population stochastic models of skeletal muscle: implications and predictions. *Biol. Cybernetics* **36**, 73–85.

Elble, R. J. & Randall, J. E. (1976). Motor unit activity responsible for 8 to 12 Hz component of human physiological finger tremor. *J. Neurophysiol.* **39**, 370–383.

Furness, P. (1977). Reduction of peak frequency of the 8–12 Hz component of tremor of human hand muscle by cooling of the muscle nerve. *J. Physiol.* **269**, 31–32*P*.

Gottlieb, S. & Lippold, O. C. J. (1983). The 4 to 6 Hz tremor during sustained contraction in normal human subjects. *J. Physiol.* **336**, 499–509.

Halliday, A. M. & Redfearn, J. W. T. (1954). The effect of ischaemia on finger tremor. *J. Physiol.* **123**, 23*P*.

Halliday, A. M. & Redfearn, J. W. T. (1956). An analysis of the frequencies of finger tremor in healthy subjects. *J. Physiol.* **134**, 600–611.

Lakie, M., Walsh, E. G. & Wright, G. W. (1983). On tuning a physiological tremor. *J. Physiol.* **334**, 32–33*P*.

Lance, J. W. (1970). *A Physiological Approach to Clinical Neurology*. London: Butterworth.

Lippold, O. C. J. (1952). The relation between integrated action potentials in a human muscle and its isometric tension. *J. Physiol.* **117**, 492–499.

Lippold, O. C. J. (1970). Oscillation in the stretch reflex arc and the origin of the rhythmical 8–12 c/s component of physiological tremor. *J. Physiol.* **206**, 359–382.

Lippold, O. C. J. (1973). *The Origin of the Alpha Rhythm*. London: Churchill Livingstone.

Marshall, J. & Walsh, E. G. (1956). Physiological tremor. *J. Neurol. Neurosurg. Psychiat.* **19**, 260–267.

Milligan, P. & Lal, S. (1982). Chance coincidence and the modelling of k independent neural spike trains. *Mathematical Biosciences* (in the Press).

REITZ, R. R. & STILES, R. N. (1974). A visco-elastic mass mechanism as a basis for normal postural tremor. *J. appl. Physiol.* **37**, 852–860.

STILES, R. N. & RANDALL, J. E. (1967). Mechanical factors in human tremor frequency. *J. appl. Physiol.* **23**, 324–330.

SUTTON, C. G. & SYKES, K. (1967). The variation in hand tremor with force in healthy subjects. *J. Physiol.* **191**, 699–711.

TAYLOR, A. (1962). The significance of grouping of motor unit activity. *J. Physiol.* **162**, 259–269.

WALSH, E. G. & WRIGHT, G. W. (1982). A hanging-hand tremorograph. *J. Physiol.* **329**, 1–2*P*.