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Postural and resting tremor in the upper limb

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Abstract

Objective: Tremor from multiple segments of the upper limb was recorded under postural and resting conditions. The aims of this study were to examine the nature of tremor within a single limb segment, intra- and inter-limb co-ordination of tremor, and the influence of cardiac mechanical events on physiological tremor.

Methods: Tremor was recorded from eight healthy adult subjects during a postural pointing task where the level of support for the upper limb segments was successively increased. The dynamics of tremor within a single segment were examined using power spectral, ApEn and amplitude analyses. Inter-segment tremor relations were determined using coherence and Cros-correlation analyses.

Results: Single segment analysis demonstrated that each (unsupported) limb segment contained two major frequency peaks (at 1–4 Hz and 8–12 Hz). Both peaks were still evident in the distal segments when the proximal segments were supported. External support of the more proximal limb segments also resulted in decreased finger tremor, but these changes were not simply additive over segments within a limb or equal across fingers. There were significant relations between adjacent proximal and distal limb segment pairs but no correlations between contralateral limb segments or between heart rate and limb tremor.

Conclusions: These findings imply that: the low frequency component (1–4 Hz) of physiological tremor in the hand and finger could not be attributed to passive transmission of oscillations from the upper arm and forearm; and the contribution of proximal segments on tremor in the index finger tremor could not be predicted from mechanical principles alone. The minimization of finger tremor involved compensatory coupling of segments of the upper arm with particular emphasis upon active control of the wrist joint.

Keywords: Resting tremor; Postural tremor; Compensatory synergy; Degrees of freedom

1. Introduction

Physiological tremor is considered a ubiquitous property of the neuromuscular system that arises from the complex interaction between neural and mechanical (limb) events (Findley and Capildeo, 1984; Elble and Koller, 1990). Examination of tremor has typically been restricted to oscillations within a single limb segment (although even the tip of the index finger in postural tremor tasks has technically more than one biomechanical degree of freedom). The common practice has been to externally support the more proximal segments of the upper limb when examining both postural and resting tremor in distal effectors (see for example: Stiles and Randall, 1967; Yap and Boshes, 1967; Marsden et al., 1969; Fox and Randall, 1970; Stiles, 1980; Homberg et al., 1987). It has been assumed that the inclusion of more proximal limb segments in the postural task merely produces a resultant tremor profile in the distal effector that represents the summed output from the coupled biomechanical degrees of freedom (Stiles and Randall, 1967; Elble and Randall, 1978; Walsh, 1992).

The view that the tremor in multi-link segments is primarily the product of mechanical coupling is challenged, however, when one considers the control of limb oscillations during tasks where an explicit external goal is required, such as in target shooting (Arutyunyan et al., 1968; Lakie et al., 1995) or pointing at a specific extrinsic target (Lacquanti, 1992; Levin, 1996). Indeed, the within-limb synergy reported during target shooting has been characterized as a compensatory neurally-driven coupling of proximal and distal limb segment pairs of the upper limb (Arutyunyan et al., 1968), a result which is directly comparable to the synergy observed during postural pointing tasks where no external reference goal has been specified (Morrison and Newell, 1996, 1999). The coupling synergy

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employed in both of these tasks is organized about the wrist joint, with compensatory motion evident between the proximal (upper arm/forearm) and distal (hand/finger) limb segment pairs. It has been suggested that this pattern of coupling achieves the goal of reducing distal tremor by exploiting the mechanical and anatomical properties of the individual limb segments (Arutyunyan et al., 1968; Morrison and Newell, 1996). For postural tremor tasks, this synergy would appear to be organized bilaterally since constraining the motion of a single joint within one limb affects the pattern of coupling in both limbs (even though no between-limb tremor relations emerge). This finding has prompted the suggestion that this synergy is generated centrally by a common neural control mechanism(s), the output of which is mutual across both limbs (Bernstein, 1967; Elble, 1996; Morrison and Newell, 1999).

The practice of isolating a limb segment has meant there has been few examinations of the natural co-ordination dynamics underlying the postural control of either intra- or inter-limb tremor. The control of tremor needs to be considered within the general context of motor control (Bernstein, 1967; Elble and Koller, 1990; Elble, 1996), and the specific understanding of how the inherent oscillatory (tremor) characteristics are embedded within the total degrees of freedom of the system. It has been shown that the addition of degrees of freedom in some tasks may actually produce a reduction in movement variability (Arutyunyan et al., 1968; Newell and McDonald, 1994). One way to test whether the effects of limb mechanical properties are additive or compensatory on the postural tremor in the index finger would be to examine the effect of successively adding or subtracting the contribution of adjacent limb segments on the intra- and inter-limb tremor relations.

It has also generally been assumed that cardiac mechanics contribute significantly to physiological tremor in resting and, to a lesser extent, postural conditions (Marsden et al., 1969; Brumlik and Yap, 1970; Elble and Randall, 1978; Lakie et al., 1986; Elble and Koller, 1990; Elble, 1996; Gallasch and Kenner, 1997). This view is based on the premise that the limb segments are mechanically coupled together so that tremor observed in the outstretched and/or resting limb should correlate with the oscillations of cardiac events. Conversely, if mechanical coupling plays a small role in the tremor of multi-link limbs, then the ballistic effects of cardiac mechanics on tremor at the periphery may also be negligible. However, to date, there has been no direct examination of this hypothesis as research has been largely confined to the study of cardioballistics and resting tremor within a single limb segment (Brumlik and Yap, 1970; Padsha and Stein, 1973; Wade et al., 1982; Lakie et al., 1986), although Marsden and colleagues (1969) did examine this relation between the index fingers.

The aim of this study was to examine the interaction of neural and mechanical contributions to inter- and intra-limb tremor in the individual segments of the upper limbs during a postural pointing task. The key issue was how progressive support of the segments of the upper arm influenced the tremor in the index finger. A secondary issue was whether cardiac output was related to the postural and resting tremor in the multiple segments of the upper limb.

2. Method

2.1. Subjects

Eight neurologically normal adult student subjects (5 women and 3 men, mean age 20.12 years, range 19–22 years) participated in this study. All subjects were right handed, physically active and reported no known neurological disorders or any sensory, cognitive or physical impairment that could affect testing performance. At the time of testing no subject was taking any form of medication that could influence limb tremor. Subjects were also instructed not to intake any stimulants (primarily caffeine derivatives) on the day of their testing session. The Office of Regulatory Compliance, Pennsylvania State University, approved the experimental procedures used in this study and written consent was obtained from each subject.

2.2. Apparatus

Eight uniaxial Coulbourn (T45-10) accelerometers were positioned on the right and left upper limbs, on the following anatomical landmarks (from proximal to distal): the upper portion of the upper arms – approximately 3 cm lateral to the belly of the biceps brachaii muscle; on the forearms – the belly of the brachioradialis muscle; on the hands – midway down the shaft of the third metacarpal bone; and on the dorsal distal aspect of each index finger. The accelerometers measured the oscillations of the limb segments in the vertical plane of motion. A ninth accelerometer was positioned 2 cm below the xiphoid process of the sternum. This accelerometer was used to provide a measure of heart rate by directly measuring the vibrations, caused by the closing of the heart valves, transmitted across the chest wall.

2.3. Procedures and design

Subjects participated in 5 experimental conditions that were completed within a single session. These conditions reflected different levels of postural support and were: full limb support (TS) where the entire upper limb was externally supported; upper arm support (US) where the upper arm of each segment was supported only; forearm and upper arm support (UF) where the forearm and upper arm were supported; upper arm, forearm and hand supported (UH); and no support, control condition (CL) where no limb segment was externally supported. Fig. 1 illustrates the experimental setup for the UH condition.

Eight trials were performed for each condition and each trial lasted for a period of 30 s. The order with which the

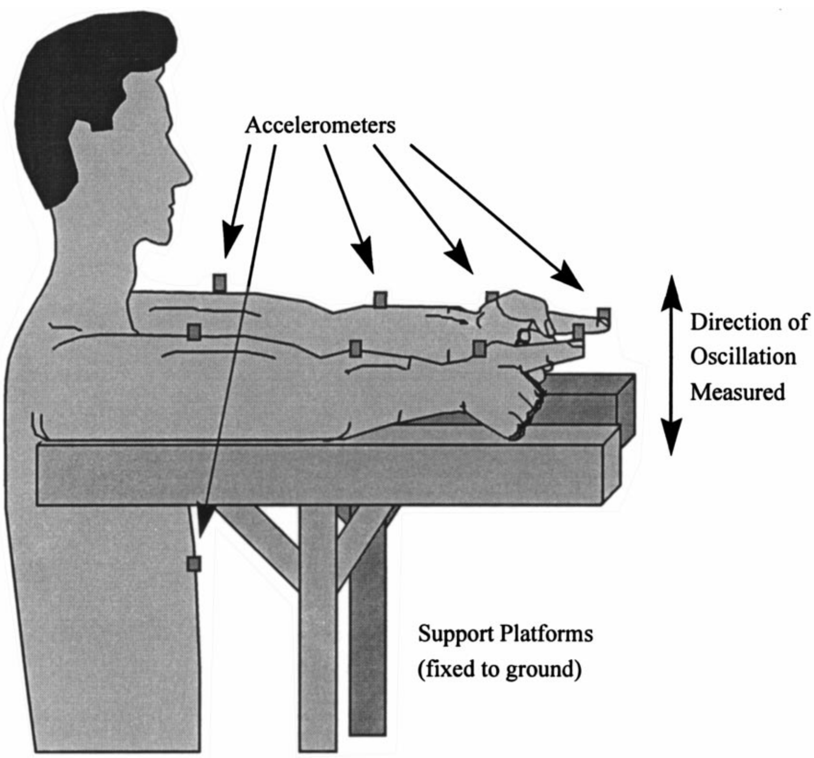

Fig. 1. Schematic diagram of experimental setup showing the position of the support and body during the UH condition, that is, where all segments of the upper limb except the index fingers were supported.

conditions were presented was randomly assigned to subjects with the stipulation being that each subject start with the non-supported, control (CL) condition. The level of support was increased or decreased progressively in either a proximal-to-distal or distal-to-proximal direction.

Under all conditions the subjects were required to stand with their arms parallel to the ground and the fingers pointing directly ahead. The positions of the upper limbs were as follows: shoulders flexed 90° in the sagittal plane, elbow fully extended, forearm pronated, the wrist was held in the neutral position. Within the hand, the index finger was extended at the metacarpophalangeal joint with the thumb adducted and fingers 3, 4 and 5 flexed, these digits forming a loose fist. The task goal, which was made explicit to the subjects, was to minimize motion of the tips of the index fingers.

Accelerometer calibration involved zero balancing each accelerometer in DC mode in a horizontal position on a level (calibration) surface. In addition, all accelerometers were mounted on the support surface to determine the (resonant) properties of this surface and whether these properties would significantly influence the measures of limb tremor when a segment was supported. No significant frequency peaks were observed for the accelerometer signals for either the calibration of support surface. No significant difference between the level (calibration) surface and support surface were found. Each accelerometer signal was amplified through a Coulbourn transducer coupler (S72-25) with an excitation voltage of 5 V and a gain of 1000. Acceleration data were sampled at 100 Hz and collected on a 386 IBM-compatible computer through a 12-bit analogue-to-digital converter. A signal-to-noise ratio of approximately 10:1 was observed for all accelerometers. The acceleration data were subsequently filtered using a Digital Butterworth low-pass filter with a cut-off frequency of 30 Hz. This cut-off frequency was selected since there is little power in the frequencies of postural tremor above this value (Elble and Koller, 1990; van Emmerik et al., 1993).

2.4. Data analysis

The acceleration data were analyzed in both the time and frequency domains as a function of limb segment, level of limb support, and trials. Data analysis was structured into two sections related to either single segment or multi-segment tremor.

2.4.1. Analysis of individual segment tremor

The frequency profile of each tremor signal within the 0–30 Hz range was determined using power spectral analysis. The frequency profile for any limb segment contains at least two prominent peaks which arise from different sources (Marsden, 1984; Elble and Koller, 1990; van Emmerik et al., 1993). In order to examine the nature of each prominent peak, the frequency analysis was performed for 4 specific bandwidths, 0–1 Hz, 1–7 Hz, 7–17 Hz and 17–30 Hz. The

0–1 Hz bandwidth was selected primarily to examine those lower frequency events such as heart rate and respiration rate that may be seen below 1 Hz. An upper 95% confidence line was calculated to determine which frequency peak(s) were significantly greater than the background level.

Two time domain analysis techniques were applied to the tremor data. First the signal was rectified and the (absolute) mean and standard deviation of tremor amplitude for each segment was determined. Second, analysis of the structure or regularity of the accelerometer (tremor) signal was conducted using a measure of approximate entropy (ApEn) (Pincus, 1991). This analysis was performed on the raw (unrectified) data. Signals that are random in nature produce an ApEn close to two while lower values (tending towards zero) would be observed for signals which display high regularity in their time series profile. In the context of the current task, a lower ApEn is assumed to reflect more active control being exerted at the joint that controls the respective limb segment. Thus, this analysis provides a measure that determines the regularity or 'complexity' of the tremor for each limb segment.

2.4.2. Inter- and intra-limb analysis

The coupling between ipsilateral and contralateral limb segments was assessed in the time domain using Cros-correlation analysis. This analysis was performed between all possible paired limb segment combinations using time lags of ± 500 ms.

The degree of between- and within-limb segment coupling was assessed in the frequency domain through coherence and phase analysis (Jenkins and Watts, 1968; Glasser and Ruchkin, 1976). The peak coherence and phase angle relations within each bandwidth was used as a measure of the degree of coupling between selected paired signals. An upper 95% confidence line was calculated to determine which coherence peaks were significantly greater than the background level (McAuley et al., 1997). The same frequency bandwidths used for the power spectral analysis were employed for the coherence and phase analysis.

Inferential statistical analysis included the use of within-subject, repeated measures ANOVA to determine the significance of changes in each of the dependent measures as a function of the level of support, limb segment and trials.

3. Results

An example of a typical raw (unrectified) accelerometer signal from each limb segment of both arms during the control (CL) condition is shown in Fig. 2. As expected, the (absolute) amplitude of tremor was greater in the more distal limb segment during this condition.

3.1. Time domain analysis

3.1.1. Amplitude measures

The mean (absolute) amplitude of the tremor signal for each limb segment across the different levels of external support is plotted in Fig. 3. The results demonstrated that the pattern of intra-limb tremor was similar between left and right limbs irrespective of changes in the level of support imposed on the task. Under control (unsupported) conditions, there were significant proximal-distal differences in the level of tremor ($F(7, 768) = 213.9$, $P < 0.001$) with the tremor being greatest in the distal segments. As the level of postural support decreased, there was a significant increase in the tremor amplitude in the unsupported segments ($F(4, 768) = 121.2$, $P < 0.001$). A similar pattern of findings was obtained for an analysis of the variability (standard deviation) of tremor amplitude.

The amplitude of tremor at the fingertip increased as the level of support decreased but the data shown in Fig. 3 indicate that these changes in finger tremor are not simply additive. To examine the relative changes in mean finger tremor, the difference between tremor in the finger and that in the more proximal segments was calculated. Fig. 4 illustrates the pattern of *relative change* in mean finger tremor (with standard deviation error bars) as a function of limb support. The results show that as the more proximal segments were progressively supported, mean finger tremor decreased significantly from that observed during the control condition ($F(1, 768) = 86.35$, $P < 0.001$). However, and importantly, this decrease was not systematic with changes in (unsupported) limb mass nor was the pattern of changes in tremor amplitude similar between left and right finger. For the right finger, the greatest decrease in tremor was found when the hand and finger were unsupported (UF), with finger tremor increasing when the wrist was supported (UH). For the left finger, tremor increased when the upper arm and forearm were supported (UF) but decreased when the hand was also supported (UH). Overall, these findings illustrate that the contributions of additional limb segments to postural tremor in the index finger are not simply additive.

3.2. Regularity analysis of acceleration signals

The pattern of the approximate entropy (ApEn) values for the upper limb during the control, unsupported condition (CL) was comparable across similar contralateral segments. Within limb, there was a significant difference between the different segments ($F(7, 2926) = 63.12$, $P < 0.001$). This difference was characterized by decreased ApEn for the hand and upper arm while higher values (less regularity) was observed for the tremor in the forearm and index finger (see Fig. 5).

Increasing the level of support produced a significant change in ApEn for all limb segments ($F(4, 2926) = 54.55$, $P < 0.001$). The within-limb pattern was preserved under conditions where the upper arm segments were supported (US, UF), although ApEn decreased for each segment from control conditions. These changes were more pronounced for the hand and upper arm segments.

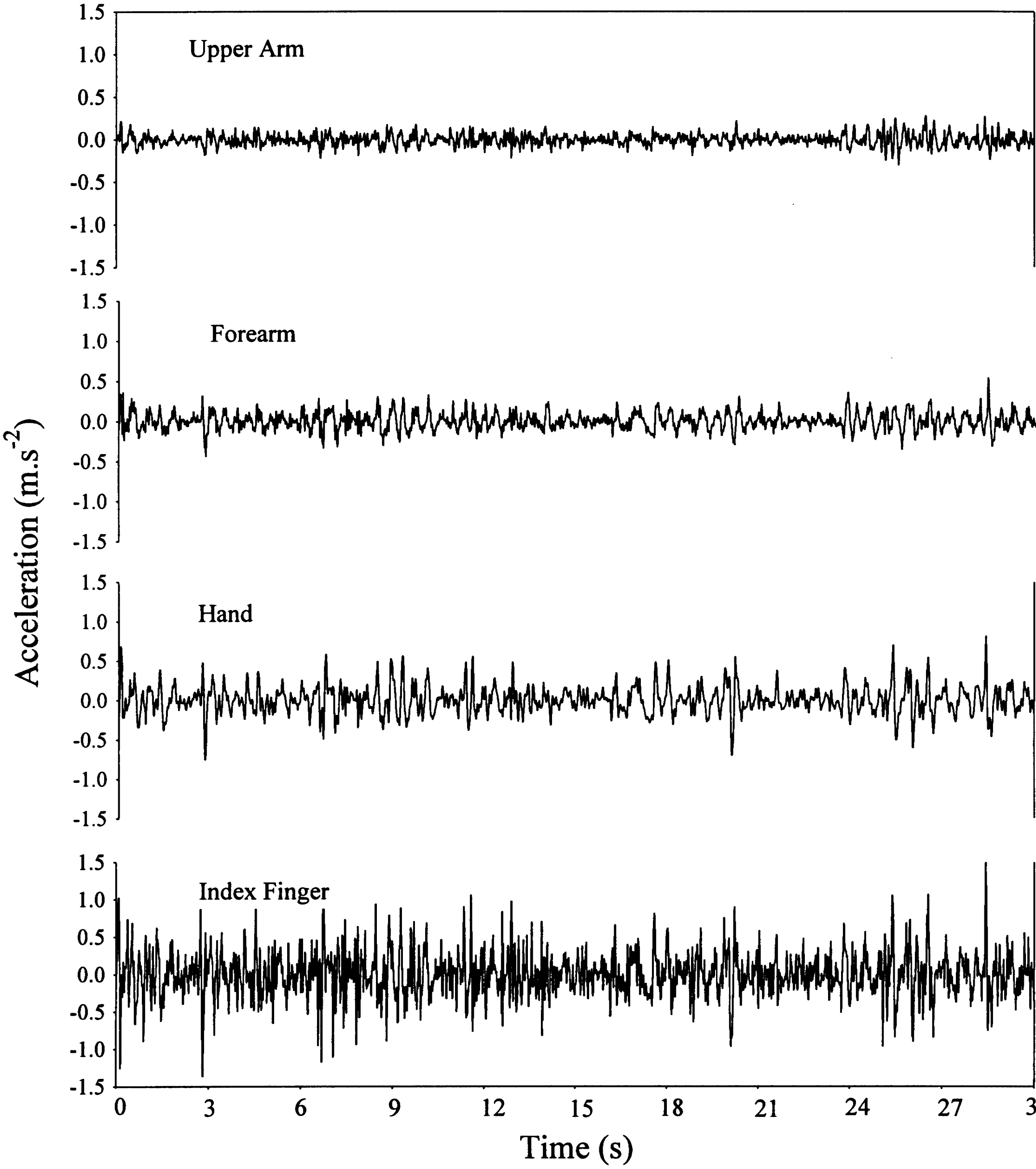

Fig. 2. Example of a typical raw accelerometer signal from each segment of a single arm during the non-supported (control, CL) condition.

No significant difference in ApEn was found between similar contralateral left and right limb segments.

Interestingly, ApEn for the hand increased under conditions where this limb segment was supported (UH, TS), indicating that there was greater regularity in the hand tremor signal under unsupported conditions. When the hand was supported, ApEn increased to a point equivalent to that of the other upper limb segments.

3.3. Frequency analysis of the tremor signal

3.3.1. Power spectral analysis

During the control, non-supported condition (CL) the tremor in each limb segment contained at least two prominent frequency peaks, one between 1 and 4 Hz and a second between 8 and 12 Hz (1–4 Hz: $F(7, 2926) = 80.18$; 8–12 Hz: $F(7, 2926) = 191.27$, $P < 0.01$). For all segments, the amplitude of the 1–4 Hz peak was typically greater than the 8–12 Hz peak. In addition, peak power increased from proximal-to-distal within limb although there were no differences in either frequency or amplitude between similar contralateral limb segments.

Externally supporting a given limb segment produced a significant change in the frequency of both the 1–4 Hz ($F(5, 2926) = 582.37$, $P < 0.01$) and the 8–12 Hz peaks ($F(4, 2926) = 51.21$, $P < 0.01$). The effects of external support were also manifested in a significant decrease in the power of both peaks within the supported segment (1–

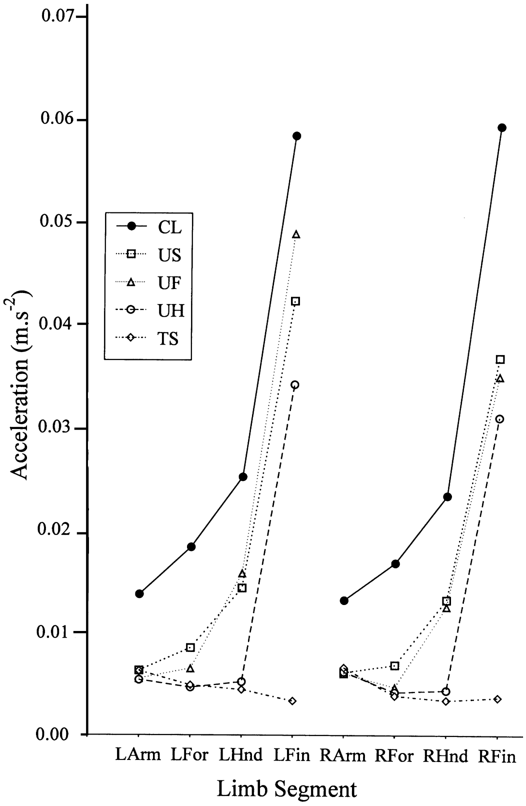

Fig. 3. The mean absolute acceleration level for each limb segment as a function of arm and the level of support. The support conditions here illustrate comparisons between the following conditions: no support (control condition, CL); upper arm support (US); forearm and upper arm support (UF); upper arm, forearm and hand supported (UH); full limb support (TS). (LArm, left upper arm; LFor, left forearm; LHnd, left hand; LFin, left finger; RArm, right upper arm; RFor, right forearm; RHnd, right hand; RFin, right finger).

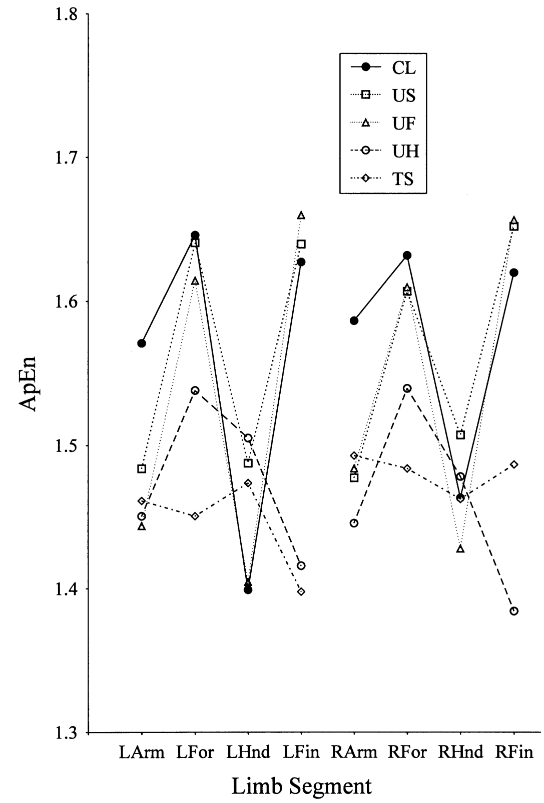

Fig. 5. Mean ApEn values for each limb segment as a function of limb segment and the level of support. (LArm, left upper arm; LFor, left forearm; LHnd, left hand; LFin, left finger; RArm, right upper arm; RFor, right forearm; RHnd, right hand; RFin, right finger). See Fig. 3 for a description of the different conditions.

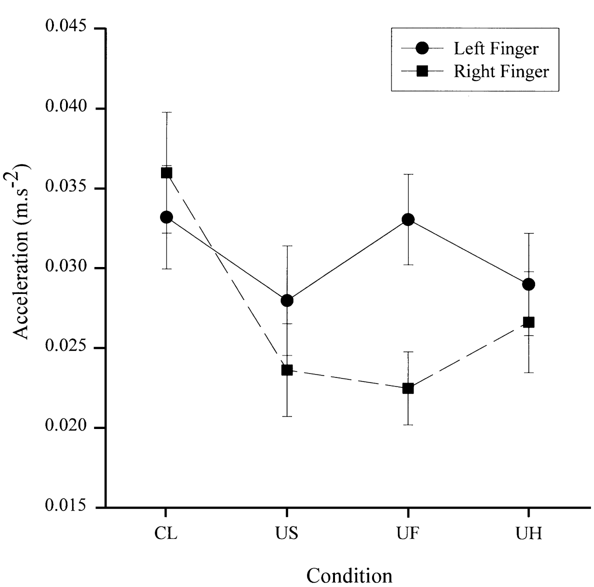

Fig. 4. The relative changes in mean finger tremor as a function of the different levels of support. See Fig. 3 for a description of the different conditions.

4 Hz: $F(4, 2926) = 43.32$; 8–12 Hz: $F(4, 2926) = 59.30$, $P < 0.01$). Interestingly, significant changes in the amplitude and frequency of the 1–4 Hz and 8–12 Hz peaks for the hand and finger were *not* evident when the more proximal limb segments were supported (UA, UF), only dropping markedly when the hand was also supported (UH). This would indicate that the large amplitude, low frequency tremor component within the 1–4 Hz range does not simply reflect the mechanical resonant properties of the more proximal segments since it was still evident even when the forearm and upper arm were supported.

The frequency profile for the index finger of each hand showed a distinct third peak around 18–22 Hz. As this peak was only observed in the index fingers, results for the frequency analysis will be limited to these effectors. Analysis showed that this peak was always present when the index finger was unsupported but that changes in peak amplitude and frequency occurred during conditions when segments other than the index finger were supported. In general, the amplitude and frequency of this peak was consistent during conditions where the upper arm and/or forearm were supported but increased significantly when the hand was also supported ($P < 0.01$). This indicates that when the hand and finger were coupled together, both the amplitude

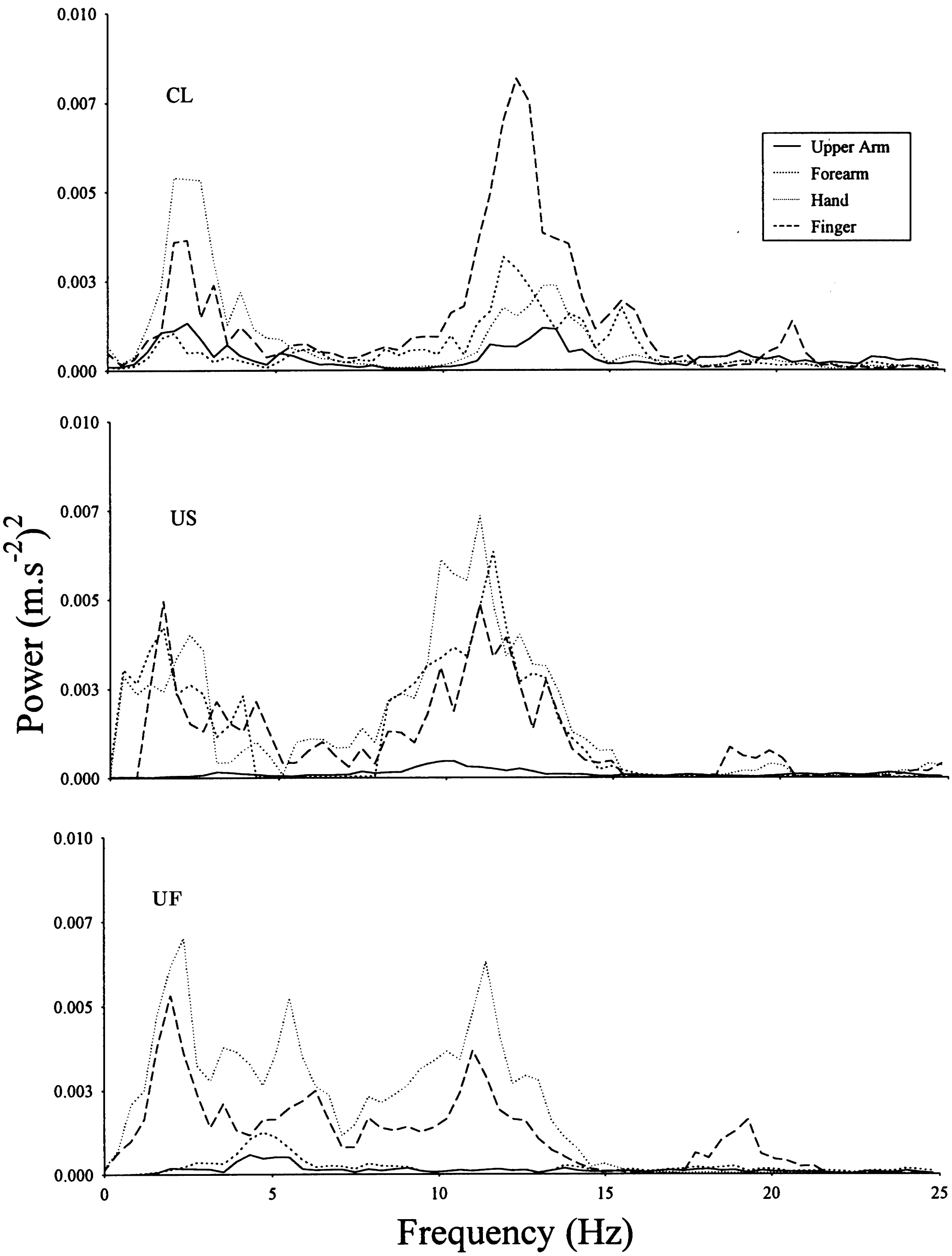

Fig. 6. Power spectral density plots for frequency of acceleration in each limb segment of a single arm during the following conditions: control, unsupported (CL), upper arm supported only (US), upper arm and forearm supported only (UF).

and frequency of the higher frequency component for the finger was reduced. Fig. 6 illustrates the changes seen in the profile of the power spectral signal for the segments of a single arm as a function of increasing the degree of external support.

No clearly distinguishable peak was seen below 1 Hz for any limb segment under any condition and as such, no results for the power spectral, coherence or phase angle analyses within this frequency range will be reported.

3.4. Intra- and inter-limb coupling of tremor

3.4.1. Correlation analysis

Cross-correlation analysis revealed significant within-limb but no between-limb relations (all inter-limb r values were $<\pm 0.25$). Accordingly, only the within-limb correlations across conditions are shown in Fig. 7 and subsequently discussed. All correlation values were converted into Z scores for inferential analysis using ANOVA techniques.

When no limb segment was externally supported (CL), significant within-limb relations were observed between the adjacent proximal (upper arm–forearm), and distal (hand–finger), limb segment combinations ($F(27, 1169) = 73.82$, $P < 0.001$). The highest relation was for the more distal combinations (left hand-left finger, $r = 0.68$–0.71; right hand-right finger, $r = 0.61$–0.70). No significant correlations were found between the forearm–hand or between non-adjacent limb segments.

Externally supporting segments of the upper limb produced a significant decrease in the strength of the within-limb correlations ($F(4, 1169) = 59.11$, $P < 0.001$) with this effect being greatest for the actual segment supported and the adjacent (distal) limb segment. A marked decrease in the hand–index finger correlation was only observed after the hand was externally supported.

3.4.2. Coherence analysis

This analysis revealed strong coupling between adjacent intra-limb segments under the non-supported (CL) condition. For the within-limb combinations, significant coherence peaks were observed at 1–4 Hz and 8–12 Hz (1–4 Hz: $F(27, 1304) = 40.32$; 8–12 Hz: $F(27, 1304) = 93.19$, $P < 0.01$). These peaks coincided with the two main peaks in the power spectrum with greatest coherence being within the 1–4 Hz range. Within-limb coherence was greatest between the following pairs: upper arm–forearm (0.93–0.94), forearm–hand (0.92–0.95) and hand–finger (0.90–0.95). Coherence between non-adjacent ipsilateral and contralateral limb segments was markedly lower (< 0.3) under unsupported conditions across the entire frequency range (0–30 Hz). This indicates that there was no coupling between any segment of the right and left limbs.

Coherence of the both peaks for the *within-limb* combinations decreased significantly as a function of increasing the level of external support (1–4 Hz: $F(4, 1304) = 40.32$; 8–12 Hz: $F(4, 1304) = 29.81$, $P < 0.01$). The greatest intra-limb decrease was between supported segments and the adjacent (unsupported) distal segment. The drop in coherence (to 0.5) was particularly marked for the hand–finger combinations when the hand and the other proximal segments were supported (condition UH). Decreased coherence was evident across all frequency bandwidths. Correspondingly, the coherence scores *between-limb* segments that were supported tended to increase slightly (<0.52). Fig. 8 illustrates the peak coherence for the significant within-limb combinations as a function of the level of external support.

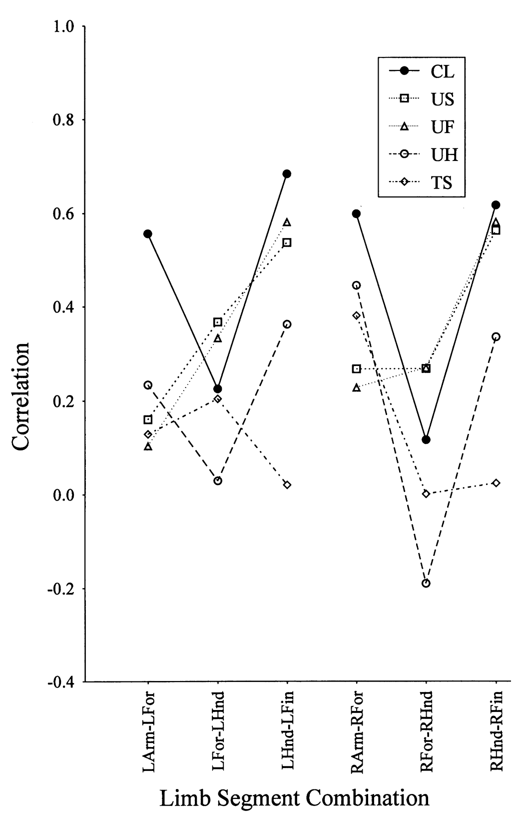

Fig. 7. The significant correlations for each adjacent limb segment combination plotted as a function of the level of support. (LArm-LFor, left arm-left forearm combination, LFor-LHnd, left forearm-left hand combination; LHnd-LFin, left hand-left finger combination; RArm-RFor, right arm-right forearm combination; RFor-RHnd, right forearm-right hand combination; RHnd-RFin, right hand-right finger combination).

3.4.3. Phase analysis

Analysis of the absolute mean and variability of the phase angle relation between limb segment pairs showed that, irrespective of the level of support, the lowest phase angle was observed below 7 Hz ($F(27, 1304) = 51.58$, $P < 0.01$). Specifically the lowest phase angles between segment pairs were observed between 1–4 Hz, coinciding with the greatest peak in the power spectrum. Under conditions of no external support, the mean phase angle for within-limb proximal (upper arm–forearm) and distal (hand–finger) segment combinations tended towards in-phase (phase angle ranges, 1–4 Hz: upper arm–forearm; ±8–35°; hand–finger; ±11–22 °). This result was also reflected by low variability about this mean (phase angle ranges: upper arm–forearm; ±7–18°; hand–finger; ±6–19°). Conversely, the mean phase angle for the forearm–hand combination under the same conditions tended to be higher (phase angle range: 80–117°) with greater variance (phase angle range: 48–65°), indicating an intra-limb relation which was compensatory (out of phase) in nature about the action of the wrist joint. Mean phase angle values tended to increase at successively higher frequencies (above 7 Hz) and between non-adjacent segments of the same limb.

Externally supporting the limb segments changed the nature of the within-limb relations, with a significant increase in the mean and variance of the phase angle between supported (proximal) limbs and the adjacent (distal) unsupported limb segment (1–4 Hz: $F(4, 1304) = 98.17$, $P < 0.01$). Significant differences were found between all conditions (all P values <0.001) except between conditions UF, UH and TS.

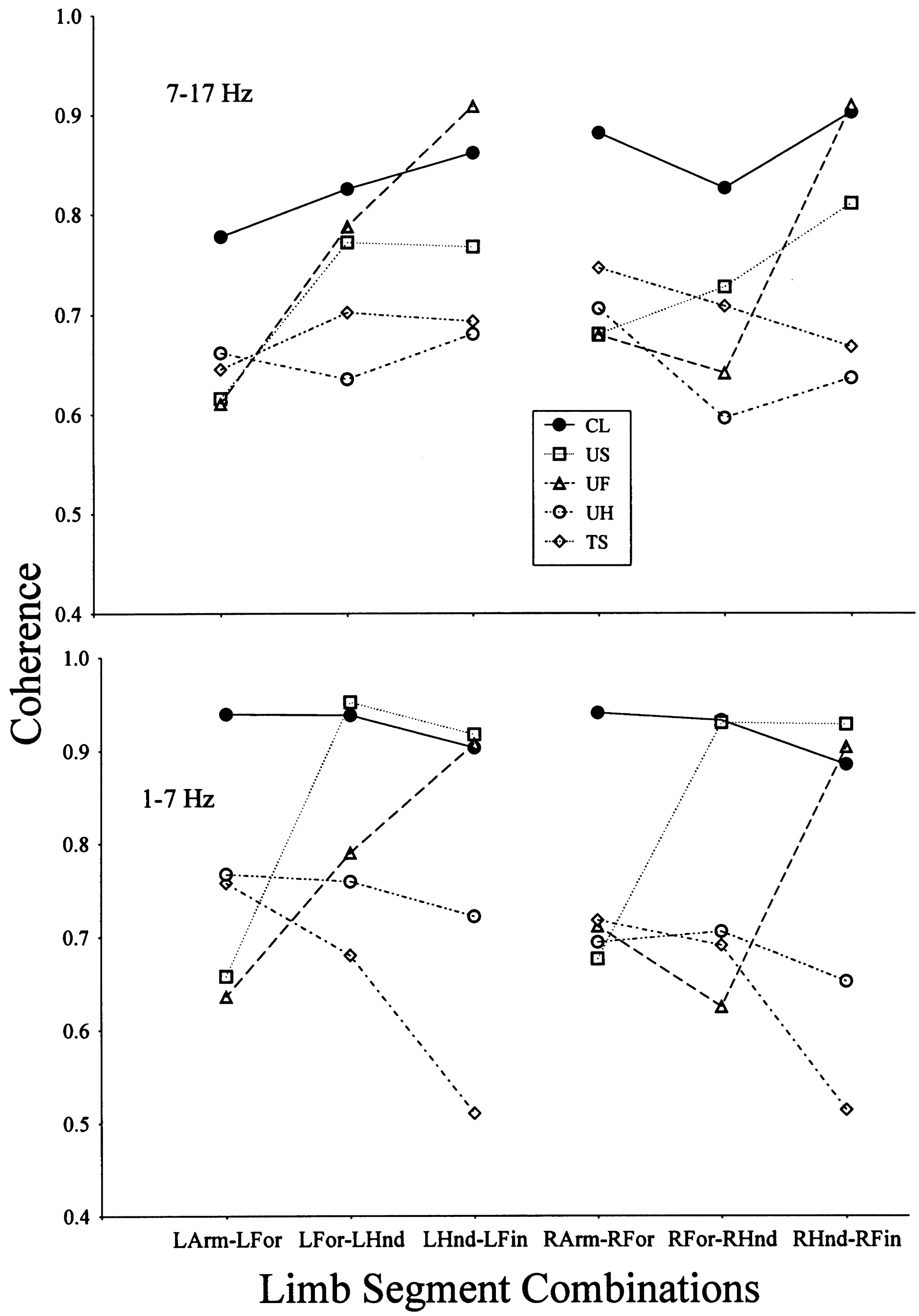

Fig. 8. The significant coherence results for the within-limb combinations of either arm under conditions of differing levels of external support. (LArm-LFor, left arm-left forearm combination; LFor-LHnd, left forearm-left hand combination; LHnd-LFin, left hand-left finger combination; RArm-RFor, right arm-right forearm combination; RFor-RHnd, right forearm-right hand combination; RHnd-RFin, right hand-right finger combination). See Fig. 3 for description of the different conditions.

3.5. Relation between heart rate and tremor

The resultant mechanical output of cardiac activity was measured by placing an accelerometer on the chest wall; a technique that has been used previously (Brumlik, 1962; Brumlik and Yap, 1970). An example of a typical raw accelerometer signal from the chest wall during the totally supported (TS) condition is shown in Fig. 9a. The mechanical output of the heart contraction clearly shows greater regularity than that observed in the tremor signal from a single limb. This observation was confirmed by both the ApEn and power spectral density analyses. The ApEn measure for heart rate was significantly lower (0.75–0.83) than that calculated for the tremor seen in any single limb segment (for comparison, see Fig. 5). Frequency analysis of the heart rate signal revealed a single dominant peak around

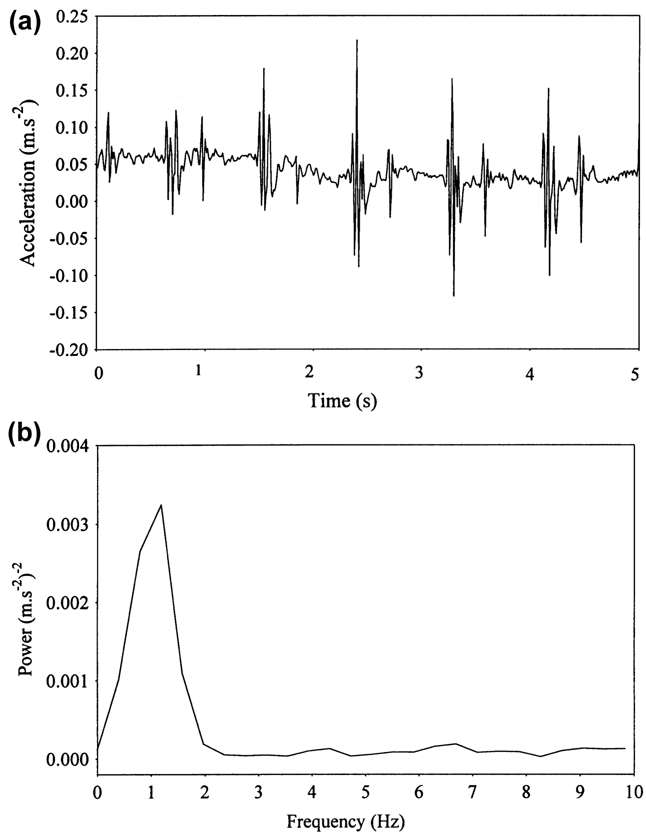

Fig. 9. (a) An example of a typical raw accelerometer signal from the chest wall during the totally supported (TS) condition, and (b) the power spectral profile for the heart rate measure for a single trial.

1 Hz that was consistent across the differing levels of limb support. The power spectral profile for heart rate during a single trial is shown in Fig. 9b.

There were no significant relations in either the time or the frequency domain between the mechanical cardiac events and the postural or resting tremor of any limb segment. No significant correlation was obtained between the amplitude of the (mechanical) cardiac events and the tremor amplitude in any limb segment irrespective of changes in the degree of external support. Generally, the correlation of these acceleration values tended towards zero. Under conditions where no limb segment was supported, the correlation between (postural) tremor in any limb segment and the heart mechanics was the lowest (r range 0.01–0.02), the degree of correlation increasing slightly (but not significantly) in each limb segment as it was supported. The highest correlation values between any limb segment and heart mechanics were observed in resting tremor where the more proximal segments of both limbs were entirely supported (condition TS), with correlation scores falling in the low range of 0.2–0.3 (i.e. less than 10% of the variance accounted for).

Analysis of the frequency components of the tremor signal and the cardiac mechanics demonstrated little coherence even under situations where the limb was fully supported (resting tremor). While the modal frequency of the heart mechanics was around 1 Hz, signal coherence within this bandwidth did not exceed 0.35. Similar coherence values (0.2–0.32) were obtained within the 1–7 Hz range, primarily between 3 and 4 Hz, but the frequency at which peak coherence was seen between heart rate and tremor in any limb segment was markedly higher than the modal frequency of cardiac signal. The peak coherence between heart rate and tremor decreased (<0.2) at higher frequencies (above 7 Hz).

4. Discussion

Postural and resting tremor were examined using accelerometry techniques under conditions where segments of the upper limb were externally supported to varying degrees in a proximal to distal direction. The hypotheses tested were that: (a) co-ordination of upper limb tremor involves compensatory coupling of intra- but not inter-limb segments; (b) interlimb coupling would only emerge as a consequence of supporting similar contralateral limb segments; (c) reducing the effective degrees of freedom through external support would decrease the *relative* amount of tremor at the finger tip and change the organization of intra-limb co-ordination, and (d) the mechanical output of cardiac events would be more strongly related to resting as opposed to postural tremor. The findings of the study revealed several new features about tremor and postural control that collectively point to the task specific nature of how tremor is embedded in inter- and intra-limb postural co-ordination.

4.1. Mechanical and neural contributions to tremor

The practice of confining tremor examinations to a single limb segment has been justified on the basis that the resultant tremor profile in the distal effector of multi-link limbs would merely represent the summed output of oscillations from the more proximal segments (Stiles and Randall, 1967; Elble and Randall, 1978; Walsh, 1992). Indeed, coupling the hand (with its greater inertia) to the finger produced a reduction in the amplitude and frequency of the mechanical (18–22 Hz) component of tremor in the distal effector, a result consistent with that predicted from previous research examining mass-tremor relations (Stiles and Randall, 1967; Elble and Randall, 1978; Elble and Koller, 1990). However, the finding here of perseverance of a prominent low frequency component (1–4 Hz) within the finger and hand tremor cannot be explained by mechanical principles alone since the more proximal segments were supported. Alternatively, it has been suggested that the presence of a low frequency component in tremor may represent a voluntary, neural component to the signal (Freund and Hefter, 1993), a suggestion which could explain the presence of the 1–4 Hz component seen here in hand/finger tremor. Furthermore, the inconsistency with which finger tremor amplitude changed as a function of the level of external support indicates that some neural control was mediating the limb oscillations in this task.

The results of this experiment show that the control of tremor in a multi-segment task cannot be explained solely by principles of mechanical coupling. Indeed, the data reveal that compensatory (out of phase) coupling between upper arm/forearm and hand/finger was initiated in order to minimize the degree of oscillation in the distal effector. This coupling required active control over the motion about the wrist in particular and was characterized here by greater regularity in the tremor signal for the hand than the other limb segments.

The adaptive nature of the complexity observed in within-limb multi-segment tremor belies the arguments for restricting the examination of tremor to a single limb segment. Moreover, since tremor itself is rarely localized to a single segment in everyday action, it is prudent to examine the control of these oscillations from a multiple degree of freedom perspective. Indeed, there is no a priori reason to assume that postural finger tremor with proximal limb segments supported provides the general or privileged window into the regulation of tremor. Even the centrally driven components of peripheral limb oscillations could be task specific.

4.2. Intra and inter-limb coupling of tremor

The performance of a pointing task under non-supported conditions was characterized by significant within-limb correlations but no significant between-limb relations. The intra-limb relations involved consistent coupling between the anatomical combinations of the upper arm–forearm and hand–index finger of each limb. This coupling was characterized by high correlation and coherence with the phase angle relation tending towards zero with little variation. The intra-limb relation between the forearm and hand was also highly correlated but the motion of the more proximal segment combination was out of phase (around $\pm 90°$) to that seen in the distal segments. This pattern of co-ordination is reflective of a compensatory synergy (Morrison and Newell, 1996, 1999), where control of the wrist joint is pivotal to reduction of oscillations at the more distal effector, the index finger. Similar findings have also been reported for the performance of pistol shooting tasks (Arutyunyan et al., 1968).

As this compensatory synergy represents a within-limb strategy used to co-ordinate the segments of the upper limb to reduce tremor in the index finger, it was anticipated that progressively supporting the limb segments in a proximal-distal fashion would change the organization of this compensatory synergy. The findings showed that the successive increases in the level of external support resulted in a decrease in the strength of the coupling between ipsilateral arm segments. Supporting the upper arm segment effectively reduced the impact of this segment to the intra-limb compensatory synergy although the hand–index finger relation was preserved.

No significant inter-limb relations were found between segments that were not externally supported, a finding consistent with that reported previously for tasks examining between-limb tremor relations (Marsden et al., 1969; Morrison and Newell, 1996, 1999). There was a gradual increase in the strength of the correlation between contralateral limb segments when the respective effectors were externally supported but these correlations were small and non-significant. Thus, the findings from this experiment extend those from previous work on inter-limb relations in postural tremor by showing that there is also no inter-limb coupling in resting tremor. It appears that the two upper limbs maintain a degree of independence in both postural and resting tremor even though they exhibit the same intra-limb pattern of compensatory organization.

4.3. Reduction of degrees of freedom

A central issue in motor control is the relation between the degrees of freedom of the system and movement variability in both joint and task space (Bernstein, 1967; Arutyunyan et al., 1968; Newell and McDonald, 1994). The traditional assumption has been that the reduction (usually by external manipulation) in the joint space degrees of freedom leads to enhanced performance (reduced variability) and, therefore, signifies enhanced control. However, this hypothesis has been recently questioned and indeed essentially reversed by proposals that increasing the degrees of freedom, for example in joint space, can reduce the variability of movement as measured in task space.

The results of this study showed that as the involvement of the more proximal degrees of freedom decreased through external support, the amplitude and variability of the tremor signal within any single limb segment decreased. However, these decreases in motion were *not* linear across the levels of support according to the length-mass properties of the respective arm segment, but rather showed non-additive changes in amplitude and variability as would be expected from a neurally driven compensatory strategy. The greatest decrease in tremor from resting (supported) position was observed when the index finger and hand were free to move. Allowing movement about the wrist joint resulted in significantly smaller tremor in the index finger. The effects of constraining the motion of the more proximal limb segments on finger tremor supports the notion that a compensatory synergy around the wrist joint plays a critical role in the control of tremor in the upper limb during postural tasks.

This conclusion is supported by analysis of the regularity of the tremor signal through an approximate entropy (ApEn) analysis (Pincus, 1991), which demonstrated greater regularity in the tremor signal of the hand when it was unsupported. The results also showed that ApEn increased when the hand was supported externally, indicating that more active control was exerted over the action of the wrist during unsupported postural movements. Thus, the pattern of change in the structure and variance of the tremor in each limb segment suggest that there is a change in the control strategy of the upper limb according to the degrees of freedom requiring control in joint space.

It is proposed that wrist joint may act as a fulcrum for the compensatory motion of the upper limb during this postural task. The action of the wrist is not locked to the motion of the upper limb for when the upper limb is supported, it still plays a significant role in the reduction of tremor at the index finger. Thus, the *addition* of specific joint space degrees of freedom in this tremor task produced a decrease in the relative degree of oscillation in the index finger.

4.3.1. Relation between heart rate and physiological tremor

The relation between the mechanical consequences of cardiac activity and physiological tremor was also examined. While the results showed that some degree of correlation did exist between the tremor seen in supported (resting) limb segments and this cardiac measure, this relation was small (<9% of the variance) and non-significant. This indicates that, for this postural pointing task, the mechanical output of the heart (as measured at the level of the chest wall) does not contribute markedly to oscillations seen in any of the resting limb segments of either arm.

The lack of a significant relation between the mechanical cardiac events and upper limb tremor contrasts with previous claims that cardioballistics influence the tremor in a resting or supported limb segment (Marsden et al., 1969; Brumlik and Yap, 1970; Wade et al., 1982; Lakie et al., 1986; Elble and Koller, 1990; Gallasch and Kenner, 1997). This discrepancy between previous research and the findings of this study may be due, in part, to methodological differences or, in particular, to the inconsistent use of standardized terminology and/or analysis techniques.

For example, studies which have reported a strong relation between cardioballistics and resting tremor have either not elaborated as to the details of the analysis techniques used (Brumlik, 1962; Brumlik and Yap, 1970) or have not employed measures such as coherence (Wade et al., 1982; Lakie et al., 1986; Gallasch and Kenner, 1997). This lack of standardization may partly explain the inconsistent reporting of association between cardiac events and tremor since those studies which have employed frequency analysis techniques (Marsden et al., 1969; Padsha and Stein, 1973) have shown that the contribution of cardiac events to resting tremor is small (10–15%). Contributions of about $<10\%$ of the variance were also observed in this study. However, an interesting point to consider is that the greatest association between cardiac events and tremor in this study was found within the 1–4 Hz range, not at the higher ranges (8–12 Hz) reported by others (Marsden et al., 1969; Brumlik and Yap, 1970; Gallasch and Kenner, 1997). The use of different measures of heart rate would also explain why Pincus and Goldberger (1994) report higher ApEn values (1.457) for the structure of the heart rate signal than that seen in this study although it should also be noted that their value was attained for infant heart rate while we examined the cardiac response of adults.

A secondary related issue that may have contributed to the inconsistency in reported findings might be that different measures of heart rate have been correlated with tremor. Traditionally, cardioballistics has been defined as the passive mechanical oscillation in various body parts caused by the (mechanical) contraction of the heart and was measured using a force/acceleration transducer attached to a distal body segment(s) (usually the lower extremity) (Starr, 1958; Talbot, 1958; Brumlik, 1962; Yap and Boshes, 1967; Brumlik and Yap, 1970). The subsequent record (ballistocardiogram) was compared with such measures as finger tremor and/or ECG recordings. However, more recent studies has seen the exclusive use of the ECG measures as indicative of the cardioballistic effect of the heart (Marsden et al., 1969; Padsha and Stein, 1973; Elble and Randall, 1978; Wade et al., 1982; Gallasch and Kenner, 1997) – even though this is not (by definition) a true measure of the ballistocardiogram nor does it provide a direct measure of the mechanical events associated with contraction of the heart (see also Brumlik and Yap, 1970). Similarly, the use of an accelerometer strapped to the chest wall does not provide a measure of the propagative result of cardiac mechanics but rather provides a direct measure of mechanical events of the cardiac mechanism at the level of the chest.

The fact that no relation was found between the mechanical consequences of heartbeat and tremor illustrates that the heart mechanics-tremor relation is not as simple and pervasive as originally believed. However, since the arterial pulsation becomes attenuated and more complex as it propagates through the vascular system, the direct measurement of cardiac mechanics at the chest level cannot measure the ballisto-cardiac effects of blood flow at the periphery. Thus some distinction between the mechanics of blood flow, cardiac events (at chest level) and tremor would appear to be warranted since the relation between these events would seem to be strongly dependent on the experimental methodology and techniques utilized to examine this question.

Overall, the findings suggest that the tremor of each limb segment is embedded in a common intra-limb compensatory synergy that is not coupled between limbs. The neural organization of this synergy effectively modulates the variability that arises from the limb mechanical properties and is specific to the constraints imposed in the tremor task.

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