Journal of the Neurological Sciences 339 (2014) 69–74

Contents lists available at ScienceDirect

Journal of the Neurological Sciences

journal homepage: www.elsevier.com/locate/jns

Load-induced changes in older individual's hand-finger tremor are ameliorated with targeting

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ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form 11 December 2013
Accepted 15 January 2014
Available online 24 January 2014

Keywords:
Postural tremor
Loading
Coordination
Visuomotor task
Coupling
Accelerometry

ABSTRACT

The purpose of this study was to investigate hand–finger tremor dynamics when a load was applied to the finger in a group of healthy older adults. Moreover, we sought to determine if projecting a representation of the subject's finger tremor on a target was capable of overcoming the effects of loading so that hand–finger interactions returned to a state that was similar to normal tremor. Eight healthy older males (67 ± 1 year) performed a postural pointing task, where tremor was assessed using lightweight accelerometers attached to the hand and finger. Tremor was then assessed when a laser pointer was attached to the finger and switched off (the load), and then with the laser pointer attached and switched on pointing at targets of 40 mm and 20 mm in diameter. The main findings of this study were that 1) loading the finger resulted in a reduction in finger tremor amplitude and increased finger tremor regularity, but no change in hand tremor, 2) loading caused increased hand–finger 8–12 Hz cross wavelet coherence and phase synchrony, and 3) pointing at different targets while the finger was loaded resulted in an increase in finger tremor amplitude, and changes in inter-segmental coupling to the extent that hand–finger dynamics reflected normal unloaded conditions. Overall, these results illustrate that the damping effects of limb loading can be offset, in part, by altering the accuracy demands of the task to make the pointing action more challenging.

1. Introduction

Physiological tremor is an involuntary property of the neuromuscular system that can be commonly observed during many postural motor tasks requiring a degree of precision. While oscillations related to tremor cannot be completely eliminated, their characteristics are modifiable by intrinsic (i.e. within the person) and extrinsic (i.e. task) factors. Intrinsic factors relate to changes in the neuromechanical system, such as the normal process of aging and/or the emergence of neurological disease [1,2]. Extrinsic factors often relate to the specific nature of the task being performed, whereby additional demands can be imposed. Some of the more common task demands that have been employed to assess tremor properties include altering the inertial properties of a segment with loading [3,4], performing the task with more than one segment [5,6] and/or manipulating the availability of visual feedback during the tremor task [7,8].

Given that the intrinsic resonant component of the limb contributes to the tremor output, loading a segment is a common means to examine tremor production. Typically the load is applied to a single segment (usually the index finger or hand) with the other segments supported. The application of a load generally leads to an increase in the amplitude and a decrease in the frequency of oscillation of that segment in healthy individuals, although this result is largely dependent on the magnitude of the weight being applied and the segment it is applied to [9,10]. Another approach used in many tremor studies is to assess the tremor relation from multiple segments simultaneously [11–13]. The basis for this approach is that, under real world conditions tremor is never localized to a single isolated segment, but instead can be influenced by tremulous oscillations from adjacent limb segments. Thus a clearer understanding of the strategy a person employs to minimize tremor under increasing task demands can be gained from examining the tremor from more than one segment.

When performing tremor tasks involving multiple segments, the neuromuscular system is faced with the challenge of coordinating the various degrees of freedom that need to be controlled while also allowing for the different oscillatory properties both within and between segments [14]. The manner in which this within-limb control of tremor is achieved is not a simple process. Previous research has reported that for such tasks, the resultant pattern is of a compensatory nature, with strong forearm–upper arm and hand–finger segment coupling organized in a reciprocal manner about the wrist joint [11,15]. Given our understanding of this pattern of coupling within the arm for

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http://dx.doi.org/10.1016/j.jns.2014.01.023

tremor tasks, it is somewhat surprising that little attention has been given to determining what effect loading a single segment (e.g., the finger) has on the coupling relations and tremor in adjacent segments (e.g., the hand). Previous reports have described a high degree of tremor coupling between the hand and finger during unconstrained postural tasks (e.g., $r^2 > 0.8$ and 8–12 Hz coherence > 0.85), indicating a strong relationship between the segments that is mediated by both mechanical and neural factors [12,16–18].

One added consideration for performing such postural tremor tasks is the specific goal of the movement being performed. Previous research has shown that tremor can be influenced by the demands of movement being performed [19]. Thus, making the task more 'goal-directed', say by adding specific external targets for which the person has to point at, could influence the strategy employed to perform the task (e.g. [7,8,20,21]). The assumption is that increasing the goal-directed demands will provide a greater challenge to the individual, resulting in changes in tremor production (ideally a reduction in tremor amplitude) and inter-segment coordination. Further, changing the demands of a multiple-segment postural pointing task while the index finger is loaded may reveal new insight to the control processes underlying hand–finger tremor.

Unfortunately, the margin for any possible reductions in postural tremor is small, with the amplitude of finger oscillation in healthy young individuals being 1–2 mm [17] or $0.2\ m \cdot s^{-2}$ [22] when the arm is extended and the subject is performing a postural pointing task. Consequently, previous studies which have assessed the potential for tremor reduction during more goal-directed pointing tasks report only minor decreases, or in some cases, subtle increases in tremor amplitude with more challenging tasks [8,20,21]. The likelihood for tremor reduction and changes in hand-finger coordination may be realized within healthy population groups where the tremor is enhanced, such as older adults [2,23]. Therefore, the purpose of this study was to investigate hand–finger tremor during a postural pointing task when a load is applied to the finger in a group of healthy older adults. It was hypothesized that applying a light weight to the index finger would not affect hand tremor, but would increase coupling between the hand and finger and subsequently alter the dynamics of finger tremor. We then sought to determine if a representative projection of the subject's finger tremor on a target was capable of negating the effects of limb loading. It was hypothesized that even though the finger was loaded, the added goal-directed demands of targeting would facilitate hand–finger tremor responses that reflect normal unloaded tremor.

2. Materials and methods

2.1. Subjects

Eight physically active, healthy older male adults (age range: 64–72 years, mean age: 67 ± 1.3 year, mass: 83.3 ± 5.6 kg, height: 175 ± 8 cm) volunteered to participate in the study. Inclusion criteria included normal, or corrected to normal vision, and a visual acuity and retinal examination by an ophthalmologist within the previous 3 months. Subjects were screened to ensure they were not using any medication that could influence limb tremor. All experimental procedures complied with the University IRB guidelines and were consistent with the Declaration of Helsinki.

2.2. Experiment design and testing procedures

Participants were asked to perform a postural pointing task with their preferred arm under four conditions; 1) *Normal postural tremor* — where the subject held the arm parallel to the floor, elbow extended, wrist neutral, index finger extended while the other digits formed a loose fist, 2) *Weighted postural tremor*, *laser off* — where a laser pointer (length 25 mm, mass 20 g) was attached to the distal end of the ventral side of pointing index finger, 3) *Weighted postural tremor*, *40 mm target* — the attached laser was turned on and subjects were asked to keep the laser within a 40 mm diameter circular target positioned at shoulder height 5.5 m away, and 4) *Weighted postural tremor*, *20 mm target* — subjects were asked to keep the laser within a 20 mm diameter circular target positioned at shoulder height 5.5 m away. At no stage were the subjects required to push a button on the laser pointer. The task goal for the normal and weighted postural tremor conditions was for the individual to focus on their index finger and to try to minimize tremor. During the target conditions, subjects were instructed to keep the laser emission in the centre of the target. Eight 30 s trials were performed for each condition, and the testing order of conditions was counter-balanced.

2.3. Instrumentation

Tremor was measured using lightweight uniaxial Coulbourn T45-10 accelerometers (mass 1.2 g, frequency response: 0–500 Hz; Sensitivity: 1 mV/V/g; Coulbourn Instrument's, PA) which were attached to the superior aspect of the pointing limb on the hand (midpoint of the third metacarpal) and the index finger (dorsal distal aspect). These positions permitted the sensing axis of the accelerometers to measure vertical oscillations of the relevant segments. Accelerometer signals were sampled at 100 Hz through a Coulbourn V72-25B resistive bridge strain gage coupler, and custom Labview (National Instruments) software.

2.4. Data analysis

All data analyses were performed using custom Matlab software (MathWorks, R2012a). Acceleration data were low pass filtered using a dual-pass fourth-order Butterworth filter with a cut off frequency of 40 Hz. Acceleration data were converted to root mean squared (RMS, bin widths 100 ms) to examine the amplitude of tremor for the hand and finger. The degree of regularity of hand and finger tremor was quantified by applying Approximate Entropy (ApEn). ApEn is a probability statistic based on the logarithmic likelihood that a sample of data will remain within a tolerance window defined as 20% of the standard deviation ($r = 0.2$) in subsequent data increments ($m = 2$) within a serial signal. ApEn approaches zero with increased signal regularity, and two with decreased signal regularity. Frequency analysis was performed on the filtered hand and finger tremor signals within the range of 0–40 Hz using Welch's averaged, modified periodogram method with a 512 data point Hanning window. This produced a frequency binwidth for the tremor signals of 0.1953 Hz. The maximum amplitude of each spectrum (peak power), and the frequency at which the peak power was observed (frequency of peak power) was calculated within a bandwidth of 5–13 Hz. This bandwidth was selected so as to isolate the major frequency components (mechanical and neural) for postural finger and hand tremor that fall between 8 and 12 Hz [24–26]. The proportion that power within this 5–13 Hz bandwidth represented across the total signal power (up to 30 Hz) was also calculated.

Estimation of the degree of coupling of tremor between the hand and finger was determined with cross correlation and cross wavelet analyses. Acceleration data were cubic spline interpolated to 1000 Hz so that phasing lags could be calculated with a minimum resolution of 1 ms. Peak correlation coefficient was used as a measure of coupling strength. Cross-wavelet analysis was used to examine the transfer function gain, coherence, and phase angle between the hand and finger in the 5–13 Hz bandwidth. The complex Morlet wavelet was employed (central frequency 3 Hz, broadband frequency 1 Hz), as it allowed the extraction of instantaneous phase differences at each position in time and frequency for tremor data. The wavelet transfer function gain was calculated as the ratio of power that is transferred from the input (hand) to the output (finger) of the system, at a given scale [27]. Wavelet coherence (WCOH) was defined as the amplitude of the wavelet cross spectrum normalized to the two wavelet power spectrums for the hand and finger. WCOH ranges from 0 to 1, and indicates the relative strength of the linear relationship between the hand and finger. In the present study, the WCOH was used to quantify the statistical reliability of wavelet transfer gain where only transfer function gains that displayed WCOH ≥0.50 were used in data analyses [28]. The average phase angle between the two signals was calculated as the circular mean of the phase differences (ΔΦ) between the hand and finger, and wrapped to the interval −180 to 180°. A negative value indicated that finger tremor 'lead' those changes observed in the hand. The time-dependent stability of the phase difference, and thus the phase synchronization index (PhSI), was calculated as:

$$\mathrm{PhSI}(a,t) = \sqrt{\langle \cos\Delta\Phi\rangle^2 + \langle \sin\Delta\Phi\rangle^2} \quad (1)$$

where $\langle\cdot\rangle$ denotes a smoothing of phase fluctuations in the time plane for the given scale (a) and time (t). PhSI ranges from 0 to 1 where value of 1 indicates perfect phase synchronization, and a value of 0 is a complete absence of phase synchronization between the finger and hand. Representative subject data for cross wavelet analysis, and the relationship with other analyses employed in this study, is presented in Fig. 1.

2.5. Statistical analysis

A within-subject, repeated measures ANCOVA was used to determine the effects of segment and condition on RMS acceleration, ApEn, and power spectral data. Each subject's baseline data was used as a covariate, and sphericity was ensured by fitting a compound symmetry structure to the mixed model. If a main effect of segment was identified, condition effects were not presented as the interpretation of grouped hand and finger data will be limited. Tukey's HSD multiple comparison tests were used to determine if the loaded conditions for each segment were significantly different to baseline tremor measures. Dependent variables from the coupling analysis were also examined using ANCOVA. Main effects and post-hoc analysis was employed to determine the effect of condition on dependent variables calculated in the between-segment coupling analyses. For all main and interaction effects, partial eta square (μ^2) are reported for effect sizes. All statistical analyses were performed using SAS 9.1 (SAS Institute Inc.) and the level of significance was set at 0.05.

3. Results

3.1. Hand and finger RMS acceleration (tremor amplitude)

A significant effect of segment was identified ($F(1,50) = 6.79$, $p = 0.012$, $\mu^2 = 0.79$), where RMS acceleration amplitude for the hand (0.10 ± 0.02 m·s^{-2}) was less than the finger (0.29 ± 0.15 m·s^{-2}). A segment by condition interaction was detected ($F(7,47) = 3.43$, $p = 0.004$, $\mu^2 = 0.82$) and planned contrasts revealed that finger tremor during the normal condition was greater than finger tremor during the weighted condition with the laser off ($t(47) = 4.05$, $p < 0.001$) and during the weighted condition with the laser pointing at the 40 mm target ($t(47) = 2.24$, $p < 0.03$, Fig. 2).

3.2. Hand and finger ApEn (tremor regularity)

A significant effect of segment was identified ($F(1,50) = 5.09$, $p = 0.042$, $\mu^2 = 0.44$), with ApEn being lower for the hand (1.35 ± 0.14) compared to the finger (1.54 ± 0.21). A segment by condition interaction was detected ($F(7,47) = 4.52$, $p < 0.001$, $\mu^2 = 0.61$) and planned contrasts revealed that finger ApEn during the normal condition was greater than finger ApEn during the weighted condition with the laser off ($t(47) = 4.63$, $p < 0.001$), during the weighted condition with the laser pointing at the 40 mm target ($t(47) = 7.31$, $p < 0.001$, Fig. 2).

3.3. Power spectra of hand and finger tremor

Although no differences were found in the amplitude of the peak power, a segment effect was identified for proportional power in the bandwidth of 5–13 Hz ($F(1,50) = 14.5$, $p < 0.001$, $\mu^2 = 0.77$). Contrasts revealed that the proportion of power for the hand ($40.1 \pm 2.1\%$) was less than the finger ($61.3 \pm 1.9\%$). A segment by condition interaction was detected for proportional power ($F(7,47) = 3.62$, $p = 0.003$ $\mu^2 = 0.78$), and planned contrasts revealed that the proportional power for the finger during the normal condition was lower than finger frequency during the weighted condition with the laser pointing at the 40 mm target ($t(47) = 2.20$, $p = 0.033$), and during the weighted condition with the laser pointing at the 20 mm target ($t(47) = 2.16$, $p = 0.039$, Fig. 2).

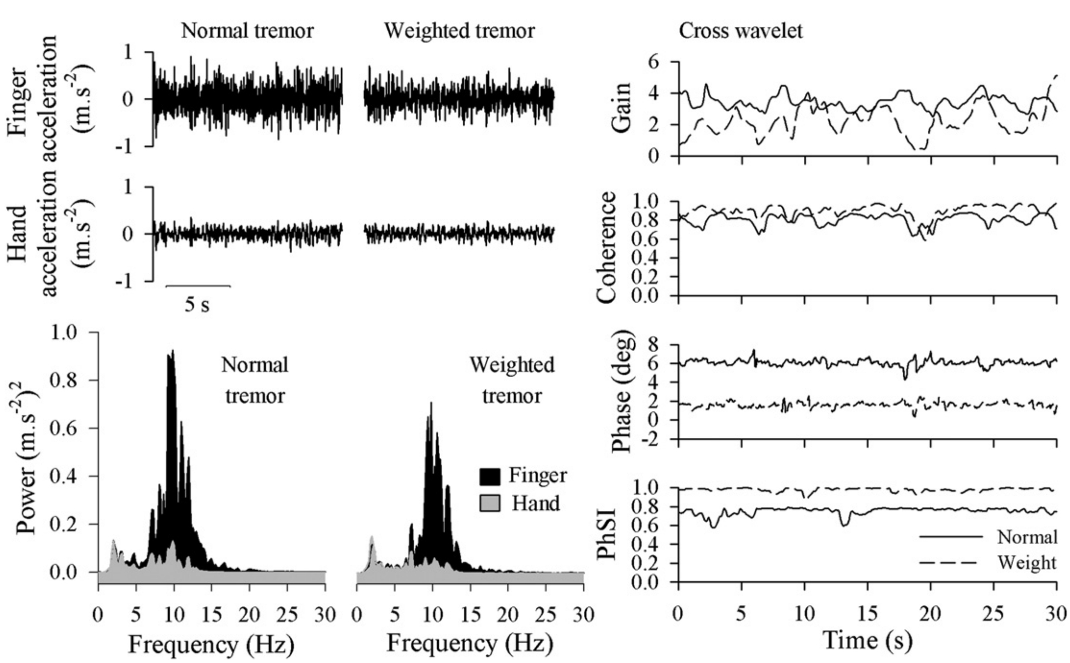

Fig. 1. Representative tremor during the pointing task, and tremor when the index finger was weighted with the 20 g laser pointer while it was switched off. Data include raw segmental accelerations (top left panels), power spectra for each segment (lower left), and measures of hand and finger coupling extracted from cross wavelets (right panels).

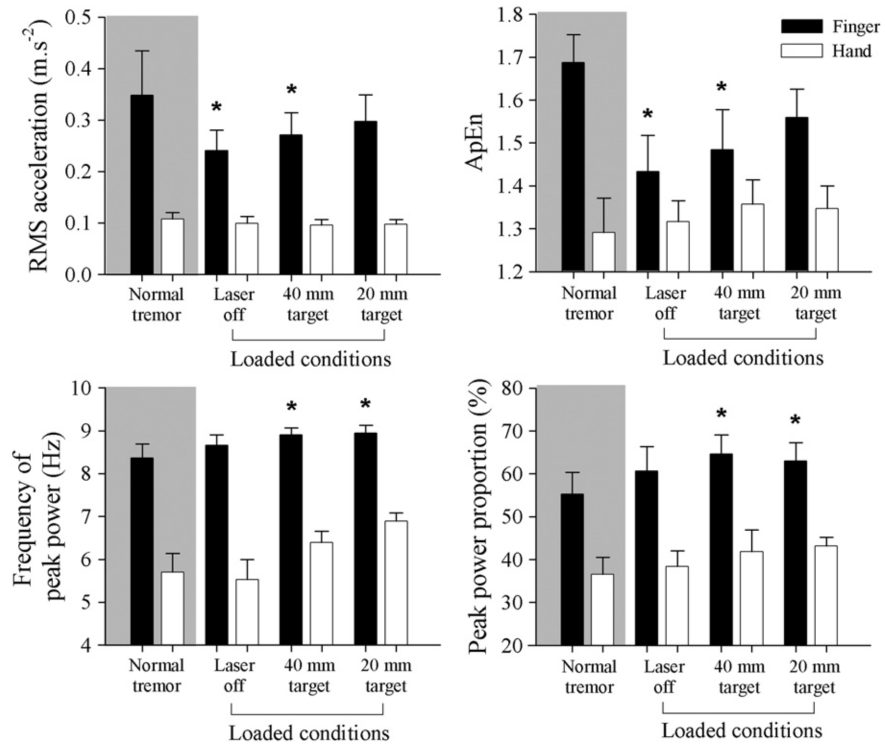

Fig. 2. Hand and finger tremor across the 4 conditions. The weighted conditions are presented for when the laser was switched off, when the laser was switched on and pointing at the 40 mm target, and when the laser was switched on pointing at the 20 mm target. Asterisk indicates that data were significantly different from normal baseline tremor for that segment.

A segment effect was identified for the frequency of peak power ($F(1, 50) = 8.51$, $p = 0.005$, $\mu^2 = 0.72$). Post-hoc analysis revealed that the frequency for the hand (6.12 ± 1.05 Hz) was less than the finger (8.71 ± 0.63 Hz). A segment by condition interaction was detected for the frequency of peak power ($F(7, 47) = 7.14$, $p < 0.001$, $\mu^2 = 0.78$) and planned contrasts revealed that the frequency for the finger during the normal condition was lower than finger frequency during the weighted condition with the laser pointing at the 40 mm target ($t(47) = 2.06$, $p = 0.045$), and weighted condition with the laser pointing at the 20 mm target ($t(47) = 2.20$, $p = 0.033$, Fig. 2).

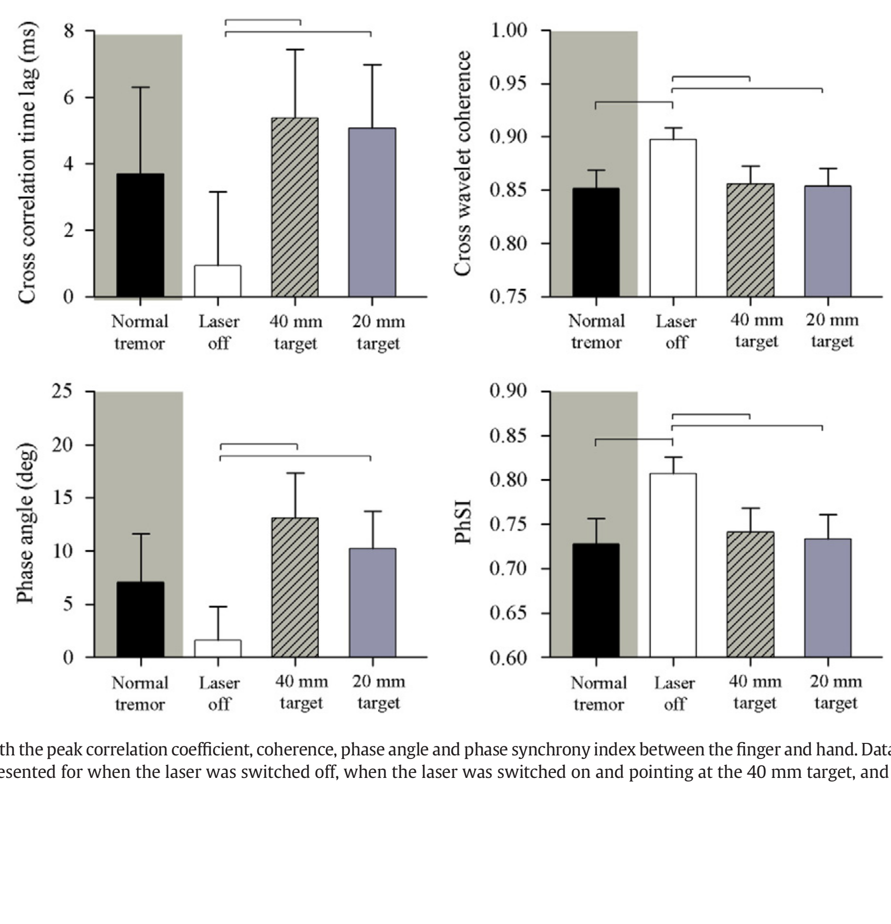

Fig. 3. The time lag associated with the peak correlation coefficient, coherence, phase angle and phase synchrony index between the finger and hand. Data is presented for the 4 conditions. The weighted conditions are presented for when the laser was switched off, when the laser was switched on and pointing at the 40 mm target, and when the laser was switched on pointing at the 20 mm target.

Similarly, the frequency of hand tremor during the normal condition was lower than hand frequency during the 40 mm ($t(47) = 2.61$, $p = 0.010$), and 20 mm target ($t(47) = 4.51$, $p < 0.001$).

3.4. Cross correlations

Although no differences were found in the peak correlation coefficients across conditions, a condition effect was identified for the time lag between hand and finger oscillations ($F(3, 23) = 3.42$, $p = 0.034$, $\mu^2 = 0.38$, Fig. 3). Post-hoc analysis revealed that the finger–hand time lag for the weighted condition with the laser off was greater than the 40 mm target ($t(23) = 2.87$, $p = 0.009$) and the 20 mm target ($t(23) = 2.67$, $p = 0.013$).

3.5. Cross wavelets

No differences were found in the gain modulus, however a condition effect was detected for cross wavelet coherence ($F(3, 23) = 3.88$, $p = 0.022$, $\mu^2 = 0.34$), where hand–finger coherence for the weighted condition with the laser off was greater than normal tremor ($t(23) = 2.91$, $p = 0.008$) as well as the laser on 40 mm target ($t(23) = 2.65$, $p = 0.014$) and the laser on 20 mm target ($t(23) = 2.77$, $p = 0.011$, Fig. 3). A main effect was also identified for phase angle between hand and finger tremor ($F(3, 23) = 1.98$, $p = 0.048$, $\mu^2 = 0.25$), where the weighted condition had a smaller phase angle for the 40 mm target ($t(23) = 2.61$, $p = 0.016$) and for the 20 mm target ($t(23) = 1.96$, $p = 0.049$, Fig. 3). In addition, a significant effect of condition was detected for the phase synchrony index ($F(3, 23) = 3.73$, $p = 0.026$, $\mu^2 = 0.33$) where synchronization between the hand and finger was greater for the weighted with the laser off compared to normal tremor ($t(23) = 2.94$, $p = 0.007$), the 40 mm target ($t(23) = 2.44$, $p = 0.023$) and the 20 mm target ($t(23) = 2.72$, $p = 0.012$).

4. Discussion

The aim of this study was to examine the impact that an external load applied to the finger had on hand–finger tremor dynamics in a group of healthy older adults. The main findings were that 1) loading the finger resulted in a reduction in finger tremor amplitude and increased finger tremor regularity, but resulted in no change in hand tremor, 2) loading caused an increase in hand-finger 8–12 Hz cross wavelet coherence and phase synchrony, and 3) pointing at the different sized targets while the finger was loaded resulted in an increase in finger tremor amplitude, and changes in inter-segmental coupling to the extent that hand-finger dynamics reflected that observed under normal unloaded conditions.

4.1. Effects of loading on tremor dynamics

While physiological tremor is a ubiquitous property of the neuromuscular system [25], its features can alter as a function of the limb segment it is assessed from. As expected, assessment of the physiological tremor for the hand and finger at baseline revealed considerable different characteristics across all conditions for the older individuals. Specifically, postural tremor from the finger was greater in amplitude (RMS acceleration) and more complex (higher ApEn) than the hand tremor. When the external load was added to the finger, there was an unpredicted decrease in tremor amplitude of the loaded finger although the amplitude of hand tremor was not appreciably altered. This decline in finger tremor was probably related to the specific mass only being applied to the distal segment (finger) while individuals were still able to compensate for the added load through the involvement of adjacent segments.

Previous studies have reported that loading the finger with 50 g or 100 g weights [29,30], or have used a similar loads to the current study, results in an increase in tremor amplitude in non-pathologic individuals. However, there have been notable methodological differences between these previous reports and our current study. The primary difference is that the previous studies have restrained and externally supported the hand so that the finger was examined in isolation [10,31]. In the current study, the entire arm was free to move. In this position, multiple muscle systems that span several joints may facilitate greater control at the distal effector by exploiting the degrees of freedom in the entire limb [16]. Indeed, given that this decrease in finger tremor was not reflected by any subsequent changes in hand tremor amplitude, it is possible that participants employed a strategy where increased control and coupling with the heavier, more proximal hand segment allowed them to minimize finger tremor. Further, because of the inherent coupling relations between adjacent arm segments, it cannot be ruled out that factors such as the damping characteristics of the limb played some role in reducing tremor [32,33].

Although the mass of the load in the current study was low, it was of sufficient magnitude to cause clear changes in the finger tremor dynamics and hand–finger coupling. During the loading task where the laser was attached but switched off, hand–finger phase synchrony increased compared to the unloaded baseline tremor. Specifically, the phase angle between segments reduced from 7° to less than 2°, which suggests that loading the finger caused the hand–finger system to become more in-phase and operate like a rigid unit. Under these conditions, there was also an increase in hand–finger coherence within the 8–12 Hz range. These changes could have been driven by central neural factors and/or increased mechanical coupling, since both the hand resonant frequency component and the descending neural drive related to physiological tremor occur within the 8–12 Hz bandwidth. It is unlikely that the 20 g load would cause the mechanical resonance component of the finger (20–30 Hz) to impact on the central neural peak, as finger resonance remains above 10 Hz even when loads of up to 50 g are applied to this segment [29]. While the neural component of segment tremor is largely believed to be load independent [10,29,31,34], the results of this study suggest that between-segment relationships appear to be load dependent.

4.2. Goal-directed task demands and tremor

A novel finding was that the load-induced decrease in older individual's finger tremor was ameliorated when specific task demands were imposed on the movement. Under conditions where an external target was displayed and subjects were asked to maintain a laser emission within the central region, tremor amplitude systematically increased with increasing difficulty. Under these conditions, the amplitude and regularity of the tremor signal during the targeting tasks were similar to those observed during the unloaded (baseline) condition. Given there were no changes in the mechanical properties of the limb during these tasks, the resultant increases in tremor would appear to be neurally driven, as both the frequency of peak finger oscillation and the amplitude (peak power) in the 8–12 Hz bandwidth were greater for the targeting conditions compared to the non-targeting conditions. While the neurophysiological mechanisms linking tremor with visual feedback are not clearly understood, it is obvious that aiming at a target manipulated tremor dynamics in the current study. Although it might be assumed that aiming at a small target would simply increase co-contraction and hand–finger stiffness [21], the coupling measures suggest that a more refined control process was present. Hand–finger time lags, coherence, and phasing parameters all indicated that even though the finger was loaded, inter-segment coordination reflected normal unrestrained tremor.

A key difference between the loaded conditions where the laser was switched off and those conditions where the laser was on, was that laser-based targeting facilitates an external focus of attention rather than an internal focus of attention [35]. Focusing on the effects of the movement rather than the segment itself has been found to consistently produce superior motor performance during goal-directed tasks [36].

For example, an external focus of attention in a throwing context (i.e. controlling multiple segments of the upper limb) leads to greater variability in kinematics for the throwing arm, but more accurate performance in throwing compared to an internal focus of attention [37]. For the current study, it appeared that the secondary task of targeting with the laser overcame the effects of the primary loading task, which was associated with changes in 8–12 Hz synchrony and coherence.

With our experiment design and the absence of a younger control group, there is limited scope to identify tremor mechanisms associated with aging. However, this was not the intent of the study and we have discussed our findings within the context of the results. Our observations are for a healthy older group and we do not speculate about age-related changes in tremor or the aging process in general. A further consideration is how the mechanical properties of the hand and finger, and stiffness throughout the entire system, were influenced by loading only the finger. Given that the hand and finger represent two resonant mass spring systems, an EMG-driven modeling approach may have provided insight to the role that hand and finger mechanical properties played in the current study, as well as further insight to the role that the CNS plays in segmental loading. Regardless, our results indicate that older individuals were able to maintain similar levels of hand tremor despite changes in finger dynamics, and manipulating the demands of the postural pointing task revealed new insight to the control processes underlying hand–finger tremor.

Conflict of interest

The authors declare that there are no conflicts of interest for the present study.

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