THE ROLE OF PHYSIOLOGICAL TREMOR IN ISOMETRIC FORCE CONTROL

by

THOMAS NOVAK

(Under the Direction of Karl Newell)

ABSTRACT

The purpose of this study was to investigate the influence of physiological tremor on isometric force scaling and hand dominance in relation to variability of isometric force control. Subjects were instructed to match a target line and minimize variability in a uni-manual isometric finger abduction task at 5%, 25%, 45%, 65%, and 85% of their maximal voluntary contraction (MVC). The experimental protocol was performed in separate blocks of the left and right hands, respectively. Physiological tremor correspondent to oscillation in the 8-12 Hz frequency band was enhanced with neural drive across all force conditions. This enhancement correlated directly to changes in both performance (RMSE) and structural variability (Sample Entropy) of the force signal. No significant findings were found between the dominant and non-dominant hands. The findings provide evidence that physiological tremor has a direct influence on the dispersion and structure of the variability of isometric force control.

INDEX WORDS: Physiological tremor, Isometric force, Motor control, RMSE, Sample Entropy, Spectral profile, Finger Abduction

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B.S., The University of Texas at San Antonio, 2013

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2016

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August 2016

DEDICATION

I would like to thank my mother Andrya Mammen for sacrificing so much, so that all of her five children were given the opportunity to succeed in every walk of life. I would like to thank my lab partners Charley Lafe, Matheus Maia Pacheco, Ichieh Lee, and Martijn Verhoeven for all of their support. It has been a real pleasure growing with all of you, and seeing how such a diverse group can come together and contribute to our individuals successes. Most importantly, I want to thank my wonderful fiancé, Victoria Seng. Your love and support is something I will never take for granted, and I could not have imagined going on this journey without you.

ACKNOWLEDGEMENTS

Thank you to Dr. Karl Newell for his continual support and guidance throughout this educational process. I have a profound respect for you, and find myself fortunate to have worked under your counsel. I would also like to thank Dr. Phillip Tomporowski, and Dr. Jarrod Call for dedicating their time to helping me with anything and everything I needed. I aspire to be as approachable as they are during such a stressful process for future students in need.

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CHAPTER 1

INTRODUCTION

There has been a growing interest in characterizing brain, muscle and movement relations through a decomposition of the respective frequency structures and their couplings (Buzsáki, 2006; Kugler & Turvey, 1987). It is well established that the large amplitude rhythmic oscillations in voluntary motor control are typically within the 0-4 Hz frequency bandwidth (Hausdorff, Zemany, Peng, & Goldberger, 1999; Miall, 1996). In this bandwidth, interactions of the magnitude of force output, perceptual information and differences in population characteristics show the greatest level of frequency and amplitude modification. Nevertheless, isometric force and postural tremor studies have shown that practice, age, visual information, and neural drive all have an effect on changes in the spectral profile out to at least 12 Hz (Deutsch & Newell, 2003, 2004).

Specific to the 8-12 Hz frequency bandwidth is a persistent, centrally driven physiological tremor that is revealed in EMG, force output, and movement data. While a plethora of literature has studied the principal sources and components of tremor (Deuschl, Bain, & Brin, 1998; Elble & Koller, 1990), the proposed relation of tremor to error correction and variability of adaptive motor output has received little experimental attention. Goodman and Kelso (1983) showed that the initiation of discrete movement is related to the dynamics of tremor. However, there is a need to examine the adaptive role of physiological force tremor across the confluence of organismic and task conditions in movement control.

Variability is an ever-present characteristic within and between all biological systems (Newell & Corcos, 1993). Traditionally, it was hypothesized that movement variability is a result of sensori-motor noise in the system, with the dispersion of variability (i.e. standard deviation (SD)) reflecting white noise stochastic processes (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Nevertheless, the use of non-linear dynamical analysis techniques has provided evidence that these variations in motor learning and control possess a high level of deterministic properties that are reflected in the time and frequency domains (Lipsitz & Goldberger, 1992; Slifkin & Newell, 1999).

Isometric Force Variability

The experimental study of isometric force production during volitional tracking tasks has provided insight to the role of variability in perceptual-motor coordination and control (Slifkin & Newell, 1999). Subsequent studies have revealed that the interaction between information (predominantly visual) and magnitude of force production affects the dispersion and the time-dependent variability as a function of maturity (Deutsch & Newell, 2002), aging (Ofori, Samson, & Sosnoff, 2010), disease state (Poon, Robichaud, Corcos, Goldman, & Vaillancourt, 2011), perceptual and coordinative modality (Athreya, Van Orden, & Riley, 2012), and manual dominance (Hu & Newell, 2012). The dynamic patterns in the time and frequency domain show that a number of factors have an effect on the emergent properties of force output variability. Specifically, there is a range of processes contributing to the interactions between feedback and feedforward processes culpable to motor control.

An example of this interaction is represented in an experiment conducted by Deutsch and Newell (2003). This study examined the prevailing assumption that neurological and physiological maturity results in a decrease of noise in the motor system and that reduced noise contributes to a reduction in the variability of force control with age. The experiment scaled levels of force output and manipulated visual information (feedback/no feedback) in an isometric pinch task. The findings showed that there was no relation between age and white noise in the force signal, indicating that perceptual-motor performance variability is not due to a reduction of noise in the system. Instead, the variations in the time and frequency structure of the force signal as a function of force level and visual information differed significantly with age. Notably, adults exhibited decreased structural regularity along with significant modifications of the spectral profile out to 12 Hz in the force output compared to children. It was concluded that reductions in force variability with age represent greater flexibility in using shorter timescale feedback and feed forward frequency processes for error correction.

To further investigate the time scales of isometric force variability, Deutsch and Newell (2004) examined the effect of practice on the structure of children's force variability in a pinching task without the manipulation of feedback. They found that while performing more poorly than adults, young children were able to reduce the amount of performance variability by altering the structure of their force output in consonance to older age groups. Additionally, there were minor adaptations to the faster frequencies in the spectral profile, indicating some improvement in utilization of feed forward processes to improve performance. These findings effectively demonstrate how important it is to consider several measures in conjunction with task performance for greater insight on the adaptability of the human system to accomplish task resolution.

Physiological Tremor

Physiological tremor is a pervasive bandwidth of oscillation (8-12 Hz) of motor output in healthy individuals (Elble, 2013). While the amplitude of this tremor is small compared to that of the more enhanced oscillations in the 0-4 Hz bandwidth the amplitude and frequency characteristics of its contributions to force output can be elucidated. The use of force transducers or accelerometers in conjunction with EMG in previous research has provided evidence that normal physiological tremor is a manifestation of sources of mechanical resonance, cardio-ballistic impulse, peripheral reflex loops, and central-neurogenic oscillatory processes (Allum, Dietz, & Freund, 1978; Elble & Randall, 1976; McAuley & Marsden, 2000; Stiles, 1976).

Central processes of physiological tremor reflect oscillation frequencies that are not a function of mechanical changes in the body, and share no temporal relation to peripheral reflex loops. The typical frequency bandwidth that constitutes these underlying processes in healthy populations is between 8-12 Hz, and while propositions of multiple central origins have been established, lucidity on the matter has yet to materialize (Elble & Koller, 1990; McAuley & Marsden, 2000). Nevertheless, the consistent spectral peak in conjunction with the lack of temporal feedback properties at this frequency could indicate a feedforward process associated with motor control.

The acquiescence of a multi-factorial origin in physiological tremor came to fruition via 50 years of research geared towards separation of its central and peripheral properties. In order to dissociate the two sources of contribution, various techniques have been implemented in which inertial manipulation acted as a comparator between accelerometer/ force transducer and EMG data (Allum et al., 1978; Amjad et al., 1994;

McAuley, Rothwell, & Marsden, 1997). While progress continues to be made on finding the genesis of healthy tremulous output, complications arising from various experimental paradigms and their effect on the organismic, environmental, and task constraints make it a challenge for unitary agreement on existential derivatives.

The Role of Tremor in Force Output

Modulation of mechanical contributions through limb weighting or changes in the magnitude of force production reveals through decomposition the central neurological processes in physiological tremor that persist in the 8-12 Hz frequency band. It is established that these central processes are strongly correlated with EMG activity, and specifically modulation of motor unit synchronization particularly at low force levels (Allum et al., 1978; Elble & Randall, 1976). Additionally, it has been shown that motor unit synchronization has an effect on EMG amplitude and force steadiness.

Yao, Fugelvand, and Enoka (2000) assessed the effect of differing motor unit synchronization levels on force output ranging from 5-100 % maximum voluntary contraction (MVC). Simulations found that high synchronization increased absolute variability as magnitude of force contraction increased. Interestingly, it was concluded that the 100% synchronization in the EMG data had a greater impact on lower frequencies (3 Hz) in the force output. Thus, it may be that increments in force level cause changes in synchrony, which in turn may interact with both feedback and feed forward processes associated with motor control.

Feedback intermittency (King & Newell, 2015; Sosnoff & Newell, 2005), biological maturation (Deutsch & Newell, 2003), and the effects of aging (Morrison & Newell, 2012) have all been shown to influence the spectral profile of isometric force out to 12 Hz. However, due to the respective aims of each study, none required subjects to scale their force magnitude to near maximum outputs. Nevertheless, increases in power at the higher frequencies (4-8/8-12 Hz, respectively) were apparent in healthy young adults as force magnitude was scaled up to 35% of their MVC. Considering evidence that these central processes interact at both high and low frequencies, clarity on the issue of the changing characteristics in force output profile is necessary. Greater insight is needed to determine changes in organization of the motor system at high frequencies as a result of the force level requirement.

Hand Dominance

There are distinctions of organizational strategies that arise from dominant and non-dominant manual force control. For instance, Semmler and Nordstrom (1995) found significant differences in motor unit synchronization between the dominant and non dominant hands of right handed subjects, with the dominant side showing both lower synchronization and significantly lower peak power in the spectral profile of the force tremor output in a finger abduction task. Semmler and Nordstrom (1998) further explored the contrast in handedness and individual differences between skill trained (musicians), resistance trained, and un-trained subjects in the same isometric force task. They found that skill-trained subjects had significant differences in motor unit synchrony, with both the dominant and non-dominant hand showing low synchrony. In addition, strength trained individuals had significantly higher synchrony in both hands compared to un-trained individuals. Furthermore, the skill-trained subjects had significantly lower tremor amplitude and lower peak power in the spectral profile of force tremor output. It was concluded that differences in the descending motor command are responsible for variations in motor unit synchrony, while differing neural and peripheral processes were responsible for changes in tremor amplitude for skill trained individuals.

These findings provide evidence that the motor system has adaptive control processes at the higher frequency bandwidths (4-12 Hz) in isometric force output. However, the experimental protocol required individuals to produce forces of 0.5 and 3.5 N that are low parameter values compared to adult maximum force capabilities. The focus of this thesis is the examination of the adaptive contribution of physiological tremor (8 to 12 Hz) to isometric force output variability over the force range.

Aims of this Study

Research in isometric force production has primarily been on force variability over a limited range of force output. The central question of this study is whether there is a relation between fast frequency processes of tremor, originally assumed to be irrelevant in respect to volitional motor control, and the representative dispersion and structural variability of the signal as a function of force level. In addition, we will examine the effect of force scaling and differing force output strategies associated with dominant and non-dominant hand output at these frequencies.

It is expected that there will be an interaction between force level and hand dominance in both the time and frequency domains of the force output due to unique adaptations of feedback and feed-forward control processes integrating to meet the task demands. Of particular interest is the impact on isometric force variability of the representative frequencies (8-12 Hz) associated with physiological tremor. Given that these processes are predominantly central in nature, their proposed impact on how subjects match a target will provide evidence that humans adaptively modulate force level through multiple processes of sensory integration.

CHAPTER 2

METHODS

Subjects

16 self-reported right-handed subjects (age: 22 ±3 years) from the student population at the University of Georgia participated in this study. The subjects were gender balanced (8 Male, 8 Female). None of the subjects were highly trained in manually dexterous tasks, recreational or competitive weight lifters, or had a previous history of any neurological disorders. Informed consent was obtained from all participants in congruence with the IRB approval from The University of Georgia.

Apparatus

The subject sat in a stationary chair approximately 23 in (58 cm) away from a 20 in (51 cm) LCD flat screen computer monitor. In front of the monitor were two Entran ELFS-B3 force load cells mounted on wooden blocks that were spaced approximately 7.5 in (19 cm) apart. Force output from each trial was amplified and sampled at 120 Hz by a 16-bit Coulbourn A/D board. The program used for this experiment was coded via C++ software.

Although there were no physical constraints placed on any of the subjects during testing, they were asked to maintain the same posture and keep their elbows, forearms, wrists, and palms flat on the surface throughout the experiment. Subjects were given a period to find the most comfortable position to maintain this posture before testing began. Feedback of the force output was given to subjects through a 20 in (51 cm) HP monitor with a resolution of 1920 x 1080 pixels. The force trace on the screen was set at a pixel-to-Newton ratio of 64 p/N, meaning that for every Newton of force produced in the load cell, 64 pixels lit up on the screen.

Procedures

Subjects were given approximately 5 min of familiarization with the experimental protocol before testing commenced. Here subjects were acquainted with how the feedback would be presented to them as they produced force on both the left and right load cells. The participants were also instructed to produce force via abduction at the distal phalanx of their index finger. While the testing hand was performing the task, subject were asked to position their non working hand in a homologous fashion relative to the symmetrical wooden block without touching the load cell. Thus, they maintained a homologous position without performing any active contraction. After subjects completed familiarization, the maximum voluntary contraction (MVC) of their starting hand was recorded over 3 trials, with a minimum 30 s interval between trials. The highest absolute of force (N) over all trials was designated as the MVC.

Starting hand was counter balanced between subjects and force level (5, 25, 45, 65, 85% MVC) was randomized for each participant and their respective hand. A total of 5 trials within each force level were performed before subject moved on to the next force condition. Figure 1 provides a representation of the experimental setup in this study. Participants were instructed to produce force on the load cell until a yellow feedback line (in pixels) matched a red target line in the middle of the screen. The duration of each trial was 20 s. In order to reduce any transient effects of fatigue, subjects were provided with as much time as they needed to recover between trials. The instructions were to initiate the next trial when they were confident that recovery was enough to perform to the best of their ability for the entire 20 s trial duration. After completion of all force conditions the subjects were given a short break before the same procedures were performed with the other hand.

During testing, subjects were instructed to minimize any deviations of their force output from the red target line to the best of their ability while ensuring that they maintain a uniform position. After completion of a trial, participants received knowledge of results (KR) of root mean square error (RMSE) of force output. RMSE is a way of normalizing the average deviation from the target by finding the difference in each sample mean (120 values/s) in the distribution, and the mean of the total distribution.

Data Analysis

The first 3 and last 2 s of each trial were removed from the time series data in order to ensure that subjects stabilized their force to the target and there was no complication from premature termination of the task. The data analysis was performed via Matlab 8.1 (Mathworks Inc.).

Task Performance. Task performance as a function of force level and hand dominance was assessed by using RMSE of the force output data within each trial.

Time-Domain Force Output Structure. Sample Entropy (SampEn) was used to determine the irregularity of the force signal in the time domain (Richman, 2000). The equation for calculating sample entropy is as follows:

$$S_e(m, r, N) = -1n\frac{\phi^{m+1}(r)}{\phi^{m}(r)} \quad \text{(Eq. 1)}$$

Where m is the distance between time series points being compared, and r is the radius that considers the tolerance of whether the data points are similar. N is the length of the time series, and ϕ is the probability that the points m fall within the tolerance range of r. In this study, m was set to 2, and the r tolerance was set to 0.2.

Frequency-Domain Force Output Structure. The frequency profile of the force signal was assessed using spectral analysis on the output data. Specific values calculated from the spectral analysis were the frequencies with the greatest amplitude (power), the absolute power of that peak within each frequency band, and the sum of all power within each respective band. The frequency analysis was partitioned into 2 separate bandwidths (0-4, 8-12 Hz). This was performed in order to separate the major components of standard slow frequency corrective processes, and the band typically attributed to physiological tremor.

Contribution of Physiological Tremor. A Pearson's product-moment correlation was used to determine the relation of physiological tremor frequency to task performance, and the time domain characteristics related to hand and force level.

Inferential Statistics. Analysis via implementation of a low pass filter on the original time series was performed in order to determine the implications of removing the faster frequencies on task performance, and time dependent structure of the force output data. A low pass filter removed all frequencies above 8 Hz, and the RMSE and SampEn were then compared to the original time series. The same procedures were performed with a low pass filter at 12 Hz. Here, a three way (2) hand x (3) data bandwidth x (5) force level ANOVA was performed. Significant differences in force variability between the 8 Hz and 12 Hz data would provide evidence for the role of physiological tremor in isometric force output.

All relevant dependent variables of the spectral profile were analyzed using a three-way (2) hand x (2) frequency band x (5) force level repeated-measures analysis of variance (ANOVA).

All statistical analyses were considered to be significant when the probability of making a type 1 error was less than 5% ($p< .05$). If the assumption of sphericity using Mauchly's test was violated, a Huynh-Feldt correction was used to adjust the statistical degrees of freedom. Only those main effects and interactions that were significant ($p< .05$) are reported. Analyses were performed using IBM SPSS software.

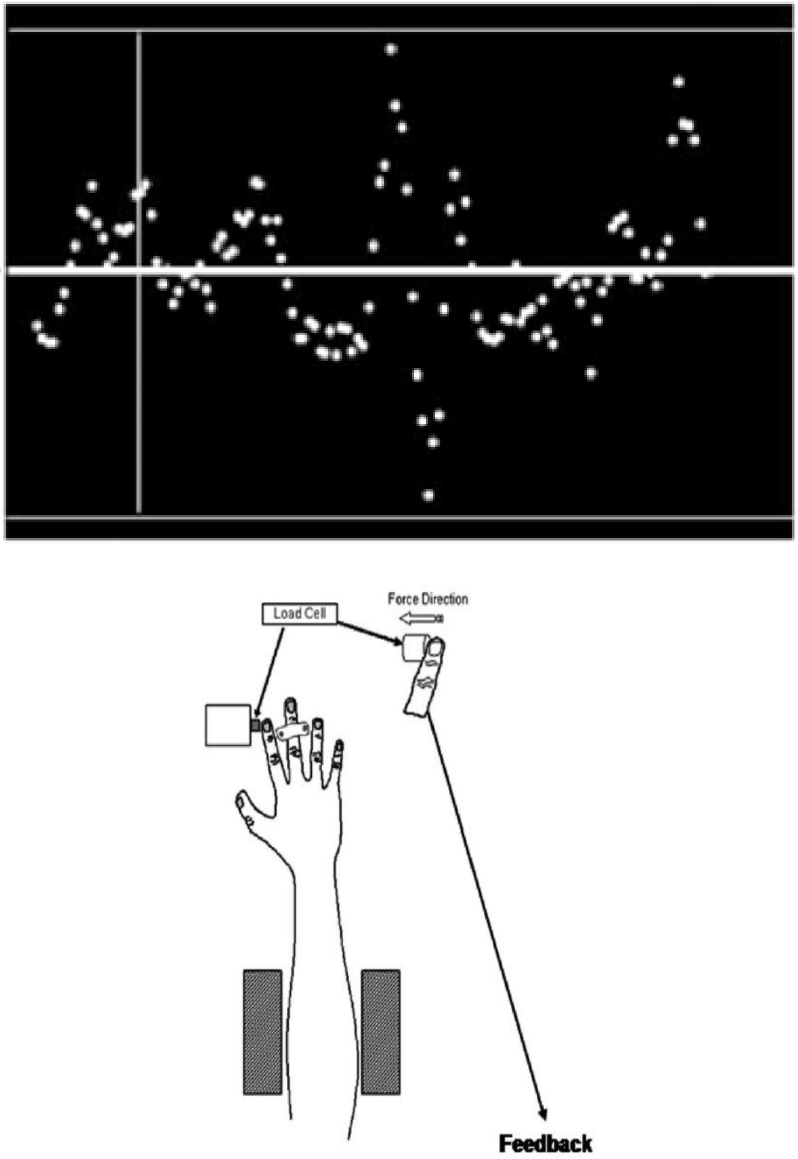

Figure 1. An example of the experimental protocol. Subjects produced isometric force by abducting their index finger. Feedback of their force output was then presented in relation to a target force (N) line. Note that this example is not exact to the experiment, with differences being in the coloration and visual intermittency of the feedback screen.

CHAPTER 3

RESULTS

The average maximal voluntary contraction of all subjects was 21.04 N (± 10.83 N) for the right, and 22.62 N (± 11.02 N) for the left hand, respectively.

RMSE Performance

Figure 2 shows the mean RMSE of force output in the original and filtered datasets as a function of hand dominance and force level. There was a significant main effect of data bandwidth: $F(1.02, 15.29)= 53.853$, $p < .001$, force level: $F(1.64, 24.63) = 78.890$, $p < .001$, and data bandwidth x force level: $F(3.16, 47.46)= 19.776$, $p < .001$ interaction on subjects' performance variability. RMSE increased in both hands as the % MVC requirement to match the target line increased. Post hoc analysis revealed that RMSE was significantly different across all force conditions except for 5 and 25% MVC in all data bandwidths.

Table 1 provides the descriptive data at all three bandwidths at every force level. While the mean differences are very small between the original (60Hz), 8 Hz, and 12 Hz filtered datasets (deviating in millinewtons), the ANOVA showed statistically significant differences in the RMSE between them. When a low pass filter was implemented at 8 Hz, the RMSE value is smaller than the 12 Hz and original data bandwidth. Additionally, the RMSE value when a 12 Hz low pass filter was utilized is still lower than that of the original time series data. Thus, the performance variability of force output is lower when physiological tremor is filtered out of the time series data.

Structure of Force Output

Figure 3 shows the mean SampEn values of original and filtered data as a function of hand dominance and force level. There was a significant main effect of data bandwidth: F(1, 15)= 355.168, $p < .001$, force level: F(4, 60)= 68.556, $p < .001$, and data bandwidth x force level: F(2.60, 39.07)= 63.949, $p < .001$ interaction regarding the Sample Entropy. Post hoc analysis revealed that the SampEn values in the original time series were significantly different across all force levels except between the 25% MVC and 45% MVC conditions. Both the 8 Hz and 12 Hz filtered data showed that the 65% and 85% MVC conditions differed significantly from all other force levels, respectively. The Sample Entropy values were the lowest in the 8 Hz filtered data, where the 12 Hz data were lower than that of the original force signal.

Power Spectrum

Figure 4 shows the representative log-log spectral profiles of the force output at 5%, 45%, and 85% MVC conditions. The frequency with the highest absolute peak power (peak frequency), the changes in that peak (peak power), and the sum of power within each respective frequency band were analyzed in order to decompose changes in the spectral profile of the force signal as a function of hand and force level. Thus, the main effects and interactions between each variable of interest are presented in the frequency bands that are representative of volitional control (0-4 Hz) and physiological tremor (approximately 8-12 Hz).

Frequency of the Peak Power. There was a significant main effect of frequency band: F(1,15) = 9149.979, $p < .001$, and frequency band x force level: F(4,60) = 4.746 $p < .05$ interaction on the frequency with the peak power in both the 0-4 and 8-12 Hz bands. Post Hoc analysis revealed significant differences between the frequency of the peak power in both the 0-4 Hz and 8-12 Hz bands across all force conditions. There were significant differences in the peak frequency at the 5% & 85%, 25% & 65%, 25 & 85%, and 45% & 85% force level conditions in the 0-4 Hz band.

Peak Power. A significant main effect of frequency band: $F(1, 15) = 25.569$, $p < .001$, force level: $F(2.43, 36.49) = 5.709$, $p < .05$, and frequency band x force level: $F(2.43, 36.50) = 5.703$ $p < .05$ interaction were shown for the peak power within each respective frequency band. Post hoc analysis revealed that the peak power between frequency bands was significant across all force conditions except for 5% of MVC. In the 0-4 Hz band, the peak power was significantly different than the 25% & 65%, and 25% % 85%, MVC conditions respectively. Significant differences in magnitude of power were present in the 8-12 Hz band between all force conditions except for 65% & 85%, indicating that the changes between magnitude of power as a function of force was more prevalent in the physiological tremor band.

Sum of Power. A significant main effect of frequency band: $F(1, 15) = 35.377$, $p < .001$, force level: $F(1.49, 22.30) = 14.275$, $p < .001$, and frequency band x force level: $F(1.49, 22.34) = 14.230$, $p < .001$ interaction was found for the sum of power within both the 0-4 Hz and 8-12 Hz frequency bands. Post hoc analysis showed significant differences in sum of power between both bands at all force conditions except that of the lowest force output requirement (5% MVC). The 0-4 Hz band had significant differences in the sum of power between all force conditions except between 5 & 25%, 5 & 45% and 65% & 85% MVC. The sum of power within 8-12Hz was significantly different across all force conditions except 65% and 85% MVC.

Figure 5 presents the relevant tremor variables as a function of hand and force level. The frequency with the peak power follows an inverted U pattern at 0-4 Hz, while a non significant increase in the left hand is observed at the frequency with the peak power in the at 8-12 Hz band with greater neural drive. While the peak frequency in the 0-4 Hz band was consistently below 1 Hz, the 8-12 Hz band showed an average increase of 1 Hz (from 9-10 Hz) with greater force requirement. Interestingly, the magnitude of the highest power and sum of power within each band shows the same trend of increasing with greater neural drive requirement.

Correlations

A Pearson's correlation analysis was performed to determine any relations that physiological tremor (8-12 Hz) may have with performance and the structure of force output.

Figure 6 provides the correlations between both force output variability (a) and the time dependent structure (b) with the peak frequency, peak power, and sum of power within the physiological tremor band. Significant correlations were found between RMSE and frequency of the peak power (right hand): $r^2 = .220$, $n = 80$, $p < .05$, RMSE and peak power (right): $r^2 = .500$, $n = 80$, $p < .01$, (left): $r^2= .575$, $n = 80$, $p < .01$, and RMSE and sum of power (right): $r^2 = .564$, $n = 80$, $p < .01$, (left): $r^2 = .582$ $n = 80$, $p < .01$.

Conversely, significant negative correlations were demonstrated between SampEn and peak power (right): $r^2 = -.243$, $n = 80$, $p < .05$, (left): $r^2 = -.421$, $n = 80$, $p < .01$, and SampEn and sum of power (right): $r^2 = -.303$, $n = 80$, $p < .01$, (left): $r^2 = -.432$, $n = 80$, $p < .01$. The strength of the correlations between RMSE and peak power, and RMSE and sum of power supports the hypothesis that physiological tremor is related to task performance.

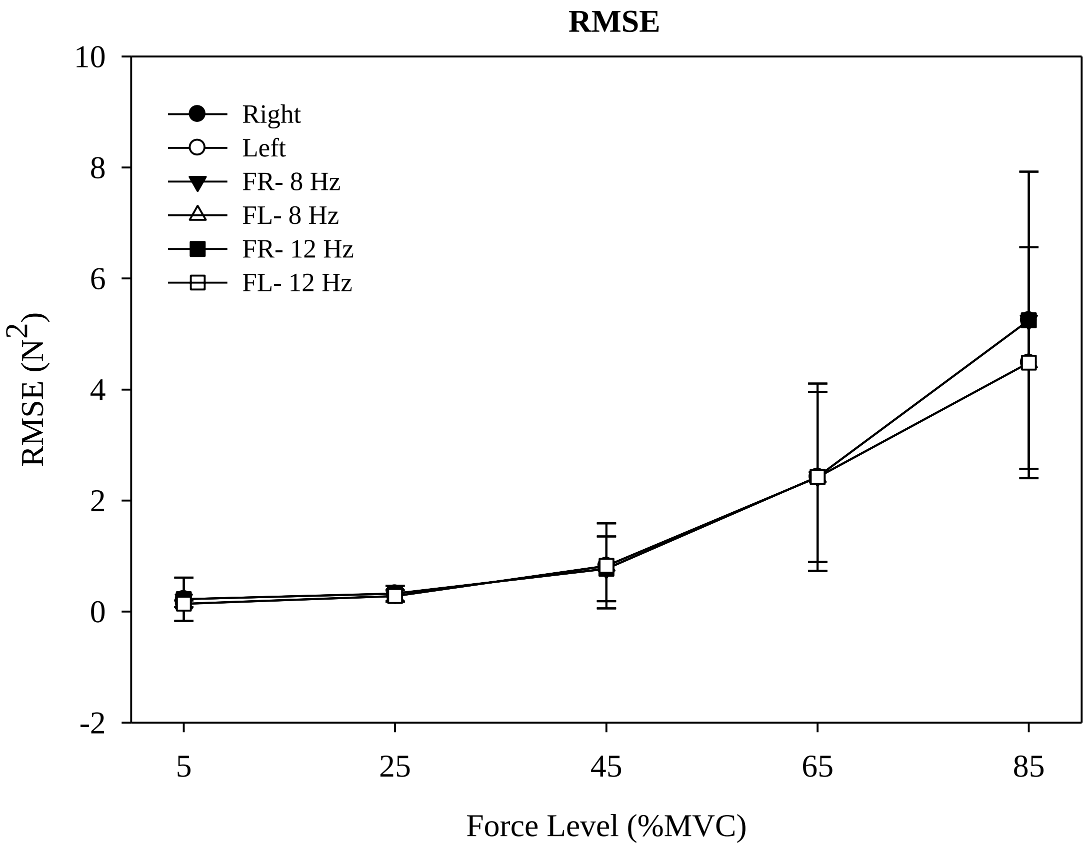

Figure 2. Root mean square error of the force signal as a function of hand and force level in the original and filtered time series datasets. The error bars represent the between-subject standard deviation (RMSE) from the mean. FR (Filtered Right Hand) and FL (Filtered Left Hand) indicate which hand is filtered at 8 Hz and 12 Hz respectively.

Table 1. Statistical analysis of RMSE as a function of hand and force level with original (60 Hz), 8 Hz, and 12 Hz low pass filtered data.

RMSE Statistical Analysis

Force Level (N)	(I) Data Bandwidth	Mean RMSE (N)	(J) Data Bandwidth	Mean Difference (I-J)	Std. Error	Sig.
5 % MVC	60 Hz	.18175	8 Hz	.001*	1.87E-04	.000
			12 Hz	.000*	7.04E-05	.000
	8 Hz	.18058	60 Hz	-.001*	1.87E-04	.000
			12 Hz	-.001*	1.19E-04	.000
	12 Hz	.18128	60 Hz	.000*	7.04E-05	.000
			8 Hz	.001*	1.19E-04	.000
25 % MVC	60 Hz	.30284	8 Hz	.003*	3.41E-04	.000
			12 Hz	.001*	1.39E-04	.000
	8 Hz	.30004	60 Hz	-.003*	3.41E-04	.000
			12 Hz	-.002*	2.06E-04	.000
	12 Hz	.30171	60 Hz	-.001*	1.39E-04	.000
			8 Hz	.002*	2.06E-04	.000
45 % MVC	60 Hz	.79803	8 Hz	.004*	4.90E-04	.000
			12 Hz	.001*	1.74E-04	.000
	8 Hz	.79452	60 Hz	-.004*	4.90E-04	.000
			12 Hz	-.002*	3.24E-04	.000
	12 Hz	.79660	60 Hz	-.001*	1.74E-04	.000
			8 Hz	.002*	3.24E-04	.000
65 % MVC	60 Hz	2.42498	8 Hz	.002*	4.32E-04	.000
			12 Hz	.001*	1.68E-04	.000
	8 Hz	2.42283	60 Hz	-.002*	4.32E-04	.000
			12 Hz	-.001*	2.68E-04	.001
	12 Hz	2.42407	60 Hz	-.001*	1.68E-04	.000
			8 Hz	.001*	2.68E-04	.001
85 % MVC	60 Hz	4.86550	8 Hz	.001*	2.37E-04	.001
			12 Hz	.001*	1.04E-04	.000
	8 Hz	4.86432	60 Hz	-.001*	2.37E-04	.001
			12 Hz	-.001*	1.36E-04	.001
	12 Hz	4.86497	60 Hz	-.001*	1.04E-04	.000
			8 Hz	.001*	1.36E-04	.001

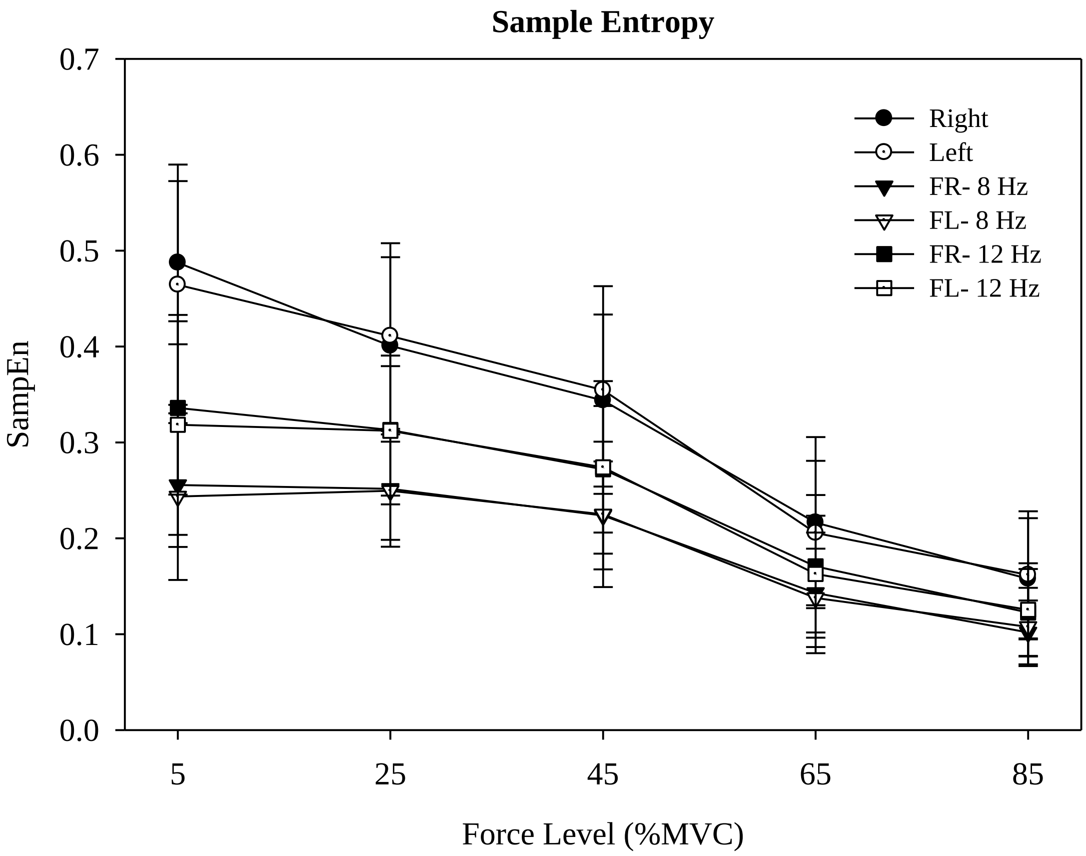

Figure 3. Mean Sample Entropy of the force output signal as a function of hand and force level in both the original and filtered time series data. The error bars represent the between-subject standard deviation. FR (Filtered Right Hand) and FL (Filtered Left Hand) indicate which hand is filtered at 8 Hz and 12 Hz respectively.

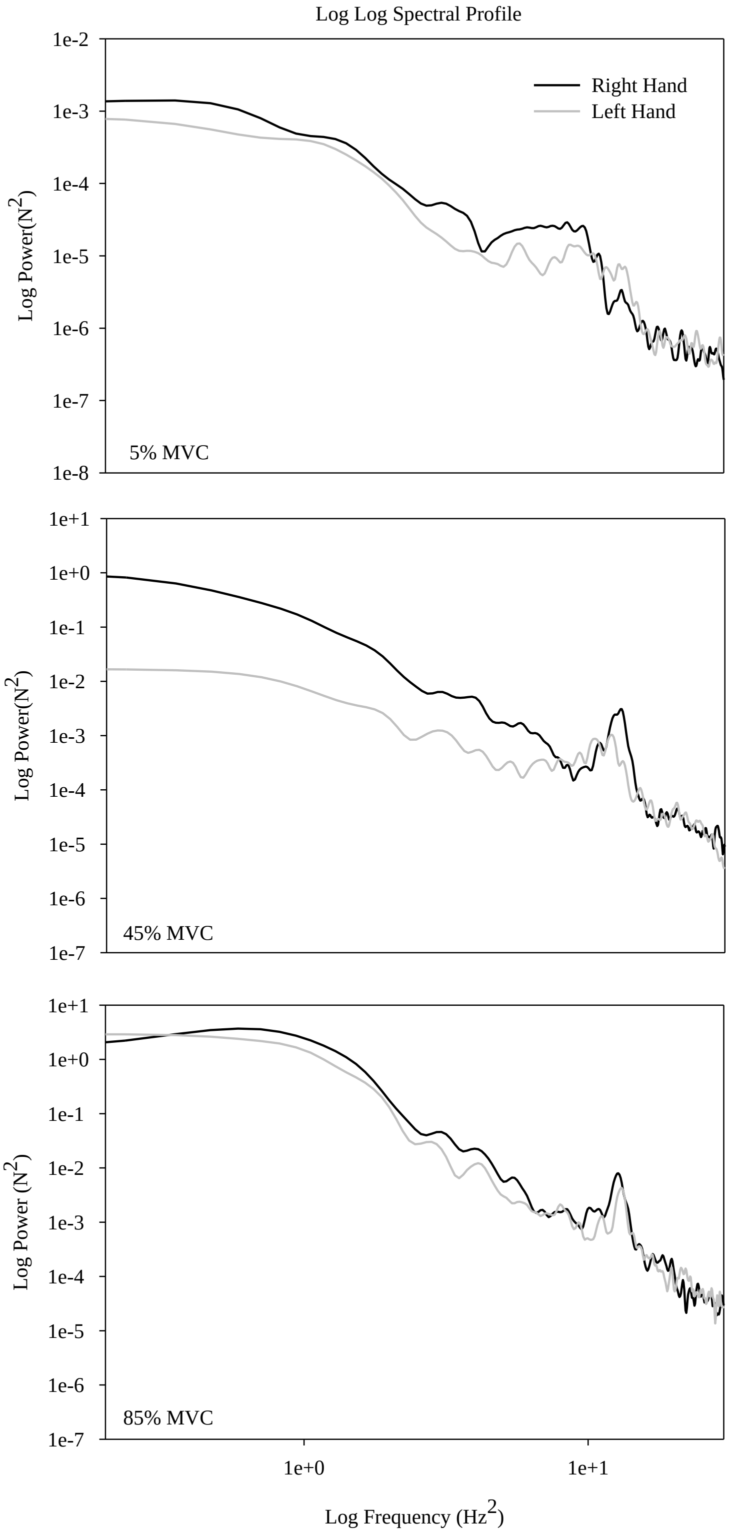

Figure 4. Log Log spectral profile of the force output from one subject at 5% MVC, 45% MVC, and 85% MVC out to 30 Hz.

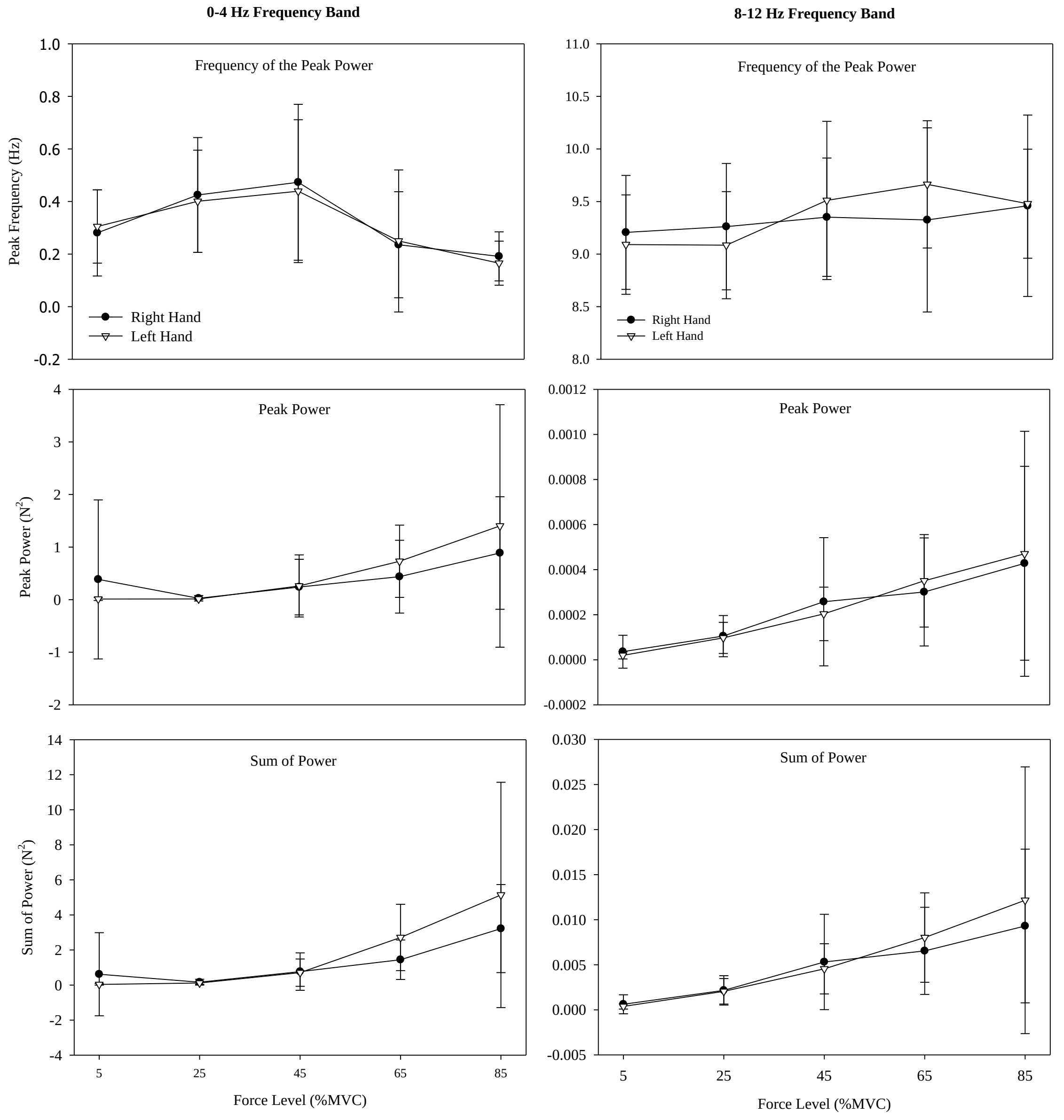

Figure 5. Mean Frequency of the Peak Power, Mean Peak Power, and Mean Sum of Power within the 0-4 and 8-12 Hz frequency band as a function of hand and force level. The error bars represent the between-subject standard deviation from the mean: Frequency of the Peak Power (Hz), Peak Power (N^2), Sum of Power (N^2).

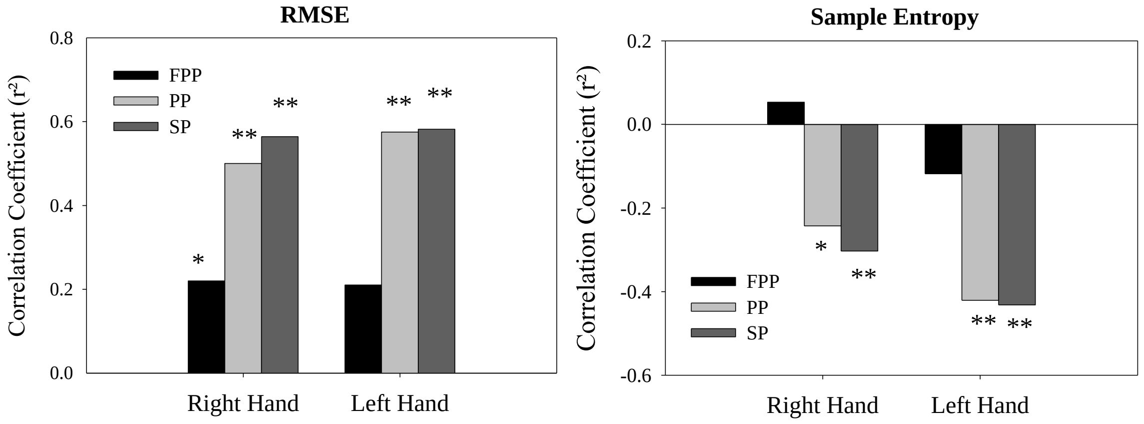

Figure 6. Correlations of Frequency of the Peak Power (FPP), Peak Power (PP), and Sum of Power (SP) between RMSE (a), and Sample Entropy (b). The symbol (*) indicates that the correlation is significant at the 0.05 level, while (**) indicates a significant correlation at the 0.01 level.

CHAPTER 4

DISCUSSION

The purpose of this study was to determine the influence of physiological tremor on the frequency structure of the variability of isometric force tracking as a function of neural drive (force level) and hand dominance. While studies have investigated force output interactions and their influence on the time scales related to sensorimotor control (Sosnoff & Newell, 2005), this is the first paper to explicitly test the influence of central-neurogenic fast frequency oscillations of physiological tremor on force signal variability. Expanding the experimental paradigm to near maximum force output capabilities addressed some key issues regarding the influence of tremor on task performance, and the impact that neural drive has on tremor.

Force Output and Performance Variability

In congruence to our expectations, the force output variability was dependent on force level requirement and the resultant neural drive (Slifkin & Newell, 1999, 2000). The RMSE of the force output was small at the low force levels, and as the force requirement moved closer to near maximal levels, the mean within-subject force variability increased in a quadratic-like fashion. The between-subject variability (standard deviation) also increased with the force level requirement.

While these findings were consistent with our expectations, it was interesting to see essentially no difference between the dominant and non-dominant hand. The Henneman principle stipulates that individuals recruit motor units in a systematic fashion based on size and physiological composition starting with slow twitch and progressing to type 2 fast twitch muscle fibers (Henneman & Olson, 1965). Although conclusions about hand dominance and performance variability are somewhat ambiguous, past studies have suggested that the dominant hand adapts a slow twitch fiber composition in order to maximize performance accuracy (Adam, De Luca, & Erim, 1998). Given that our results show minute differences between the hands in all subject’s maximum contraction capacity, and the variability between the hands is insignificant, this assertion needs to be revisited for further investigation. If the fiber composition hypothesis holds, then the behavioral variability around the target line would differ especially between the hands at the force levels surpassing postulated maximum muscle recruitment strategies (65%, 85% MVC). Thus, it may be that the constraints of the task imposed on an individual alter their dynamics strategically in a manner to help accomplish a task irrespective of motor unit composition.

Force Output and Time Dependent Structure

Previous literature has established that the structural variability of force output is not invariant, and in fact dependent on the orientation of the controlled limb (Hong, Lee, & Newell, 2007). Our study exhibited the same trend in the time dependent structure of the force output as Hong (2007), with the SampEn values decreasing systematically with increases in force scaling during isometric abduction of the index finger. Thus, as force requirement increases, the task constraints alter the dynamics of the force output in a manner that reduces flexibility of motor control strategies.

Contrary to our hypothesis, the dominant and non-dominant hands did not display any significant differences in the time dependent structure of the force output. Little research has explicitly investigated these time dependent characteristics on hand dominance. It appears that the task constraints change the organization of sensorimotor processes represented by entropy in the same manner with both hands. Hu and Newell (2011) found that bilateral interference influenced the time dependent properties of the force signal based on hand dominance in a bimanual task. Nevertheless, the uni-manual nature of our experimental paradigm shows how task specificity determines the organization of human control strategies.

Physiological Tremor in Force Scaling

In the present study, scaling of force level was shown to impact physiological tremor in a number of ways. While the frequency of the peak power significantly changed across force conditions in the slow frequency band, there was no significant change in the modal frequency at 8-12 Hz. These results provide further evidence that physiological tremor originates from a central-neurogenic oscillator that is largely resistant to variation in frequency with changes to motor system demands (Köster et al., 1998; McAuley & Marsden, 2000).

Previous studies have shown that the magnitude of physiological tremor can vary depending on level of neural excitation, drug interaction, and fatigue (Arihara & Sakamoto, 1999; Morgan & Sethi, 2005). Our investigation of the neural drive effect on physiological tremor indicates that the magnitude and sum of power in the 8-12 Hz band increases in absolute terms with force scaling. In other words, as subjects increased their force output, the physiological tremor frequencies increased their overall amplitude contribution to the force signal. Thus, while there was no change in the frequency of oscillation, we obtained the novel finding that neural drive out to near maximal force output capabilities increases the magnitude and contribution of involuntary oscillation when subjects perform a volitional tracking task.

It is interesting that the peak power and sum of power in the spectral profile both also increased with neural drive much like that of RMSE. Previous studies have linked predictive models on increased force production, physiological tremor, and increased isometric force variability to motor unit synchronization (Elble & Randall, 1976; Yao et al., 2000). While our findings are counter to this interpretation, the influence of force scaling on the tremor band was significant up to 65% MVC. Thus, more research on the contribution of physiological tremor has on synchrony, the degree to which synchrony impacts force variability, and other possible contributing factors to performance variability is necessary.

While force scaling has a definitive impact on tremor, there was no difference based on hand dominance between any of the frequency characteristics within the 8-12 Hz band. These results are contrary to those found by Semmler and Nordstrom (1995, 1998) given that our lowest force condition was comparable to the two force conditions presented in their experiments (0.5, 3.5 N), while we saw no difference in tremor frequency between the hands. These conflicting results show that future research is necessary to determine both the behavioral and physiological characteristics of hand dominance in force control, along with gaining a better understanding of how task dynamics (i.e. force scaling, vision) influence these properties in relation to tremor.

The Influence of Physiological Tremor on Force Variability

The high correlation between RMSE and both the peak power and sum of powers within the physiological tremor band are in line with the interpretation that all of them increase with force scaling. Significant correlations between SampEn and both peak power and sum of powers show an inverse relation. With increased force requirement, the tremor oscillations appear to be enhanced, while the Sample Entropy values decrease. Previous literature has concluded near maximal force output constrains individuals to reduce the possible degrees of freedom in which they can exploit during a force matching task (Keogh, Morrison, & Barrett, 2007; Svendsen & Madeleine, 2010). Still, our study presents the novel findings that neural drive in isometric force tracking increases the contributions of tremor, and these increases have a direct relationship with variability in the force signal.

The loss of complexity hypothesis stipulates that aging and disease state have a profound impact on the physiological processes utilized in human movement and control (Iyengar, Peng, Morin, Goldberger, & Lipsitz, 1996; Lipsitz & Goldberger, 1992b). Considerable evidence from this theoretical perspective has shown that physiological degradation reduces both the spectral distribution and structural irregularity of time series data. Thus, our finding that the SampEn is significantly smaller in the filtered datasets compared to the original time series reflects the loss of contributing processes occurring in the faster frequencies of physiological tremor. This loss of contribution also reflected a very small but significant change in the RMSE performance of individuals. Interestingly, the RMSE of both filtered time series data was less than that of the original force signal, with the values in the 8 Hz filtered data being the smallest. Thus, removing the physiological tremor from the signal actually improved subject performance. Still the differences are so small that these fluctuations may have gone unnoticed to subjects, and could have been modulated with alteration in the experimental paradigm. The results presented in this experiment allow us to conclude that physiological tremor has an impact on the control of isometric force. The filtering techniques provide evidence that captured the influence of tremor based on the greatest ramifications on variability coming from the 8 Hz filtered data.

Implications and Future Research

While the practical effect on performance variability with tremor is relatively small, the clinical implications in the field of microsurgery warrant its continual investigation. Micro surgical ocular, vascular, and neural interventions are utilizing new instrumentation that requires complex filtering algorithms in order to reduce involuntary oscillations from the user interface (Riviere & Jensen, 2000; Veluvolu, Latt, & Ang, 2010). The primary method in which researchers have gathered data on user tremor has been with motion accelerometer technology. However, our findings provide evidence that force transducers are a viable alternative, and may in fact be superior considering the composition of microsurgical instrumentation and the nature of user interaction. Studies have concluded that normal tremor oscillations in surgeons can reach upwards of 100 µm, while many procedures require movement precision of 10µm (Charles, 1996; Riviere, Gangloff, & de Mathelin, 2006). The proven sensitivity of force transducers via our finding of small differences in force variability provide new avenues of study geared towards continual improvement in engineering of instrumentation.

Isometric force production may also open new doors to investigating ways in which manipulation of particular task constraints can cause physiological changes to individuals at the behavioral level. For example, a considerable literature has shown how visual information, manual orientation, and synergy of the fingers and thumb impact sensorimotor organization for individuals to strategically exploit neuro-motor processes to accomplish task resolution (Latash, Shim, & Zatsiorsky, 2004; Vaillancourt, Haibach, & Newell, 2006). This is apparent in a study performed by Vaillancourt, Haibach and Newell (2006) where visual gain directly influenced the proportional contribution of frequencies at 0-4 Hz, 4-8 Hz, and 8-12 Hz during elbow flexion at various force levels. No one to date has investigated at physiological tremor directly in conjunction with how adjusting visual gain affects its influence on performance variability. Experimental data providing information on how vision, manual orientation, and grip synergy affect the contributions of physiological tremor are imperative for improving technological design and searching for optimal behavioral strategies to improve surgical success rates.

The use of accelerometers and force transducers in research towards microsurgical improvements is growing. However, the challenge of developing effective oscillatory cancelling algorithms in real time for surgical instrumentation is an ever arduous task (Ang, 2004). Great consideration should be taken with the additional fact that movement takes place in three dimensions, while many measurement techniques are constrained to one. Riviere and Gangloff (2006) found that 3-D accelerometers could detect normal tremor in surgeons close to 100μm in all three dimension. Thus, the use of three dimensional transducers and accelerometers are imperative for gaining more information about how human oscillatory processes can be changed behaviorally. This will only strengthen methods of optimizing filtering techniques and ergonomic design of instruments to eliminate detrimental oscillations while maintaining those fast frequency processes of benefit to surgical practitioners. Understanding how human tremor affects performance and force signal variability is a start. However, further research will expose new possibilities of optimizing behavioral flexibility in volitional control so that technology does not interfere with processes benefitting both surgeon and patient.

CHAPTER 5

CONCLUSION

The present paper investigated the impact of physiological tremor on the variability of isometric force control in both the time and frequency domains. While there is a significant impact on the dispersion of movement variability and the frequency structure of the force signal with force scaling, hand dominance was found to have no effect on any of these characteristics. The findings are consistent with the position that tremor is likely central in origin, and increases with neural drive.

Physiological tremor was shown to directly impact performance in this experimental isometric force paradigm. While the absolute differences in performance variability were very small, their significance is important to various applied clinical modalities in, for example, the micro surgical domain. The importance of progressing with behavioral research in conjunction with the traditional approach of technological alterations of surgical instrumentation cannot be overstated. Finally, our findings also suggest that while the relative contribution of fast frequency processes is small, they should not be treated like random artifacts in physiological time signals.

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