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VISUAL INFORMATION AND MULTIPLE TIMESCALES OF ISOMETRIC FORCE CONTROL

A Thesis in

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by

Charley W. Lafe

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The thesis of Charley W. Lafe was reviewed and approved* by the following:

Karl M. Newell
Professor of Kinesiology
Thesis Advisor

John H. Challis
Professor of Kinesiology

Kristina Neely
Assistant Professor of Kinesiology

Stephen J. Piazza
Professor of Kinesiology
Graduate Program Director

*signatures on file in Graduate School

ABSTRACT

The experiment was designed to examine the interaction between frequency of visual information feedback and force level on the control of isometric force production. Participants were asked to produce constant levels of isometric force using in separate conditions the index finger of their right hand, left hand, and both hands. Visual intermittency rates ranging from .8Hz to 25.6Hz were presented at three force levels of 15%, 30%, and 60% of the maximal voluntary contraction. There were significant effects of force level on the amount (Standard Deviation) and time dependent structure (Approximate Entropy) of force variability. Reduced intermittency of the frequency of visual feedback decreased the amount of force variability and increased the irregularity of force output. Visual information was found to have a force level dependent effect on frequency structure up to 12Hz, while spectral density was predominantly modulated within the 0 - 4Hz bandwidth. This pattern of findings for force level and intermittency remained consistent across all hand conditions. The study provides further evidence for the postulation that there are multiple timescales of isometric control that are scaled interactively by force level and visual information intermittency.

Key words: Force variability, Intermittency, Timescales, Visual-motor Processing

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CHAPTER 1. INTRODUCTION

The role of vision in the control of movement has been an area of research focus for over the past 100 years. It is well established that vision can facilitate a more accurate movement outcome during the control of limb movements, as in, for instance, reaching and manual aiming tasks. Furthermore, being able to perceive the world around you is of the utmost importance especially when trying to walk or run from one location to the next, let alone performing a skilled action as required in sporting events, such as trying to hit a pitch from a major league baseball pitcher. Woodworth (1899) realized that movement accuracy is at least partially related to visual information about the movement and its outcome. Of particular interest was the shortest movement time on which visual feedback would have an effect on movement accuracy.

Visual Control of Discrete Movements

Woodworth (1899) proposed a two-component model of manual aiming control. The first component of the model was known as the initial, or impulse phase, and the second component was the adjustment, or current control phase. This component model led to a central issue in motor control as to whether the nature of visual-motor control is continuous or discrete. The impulse phase was assumed to be the result of feedforward processes and ballistic in nature, and was used to bring the limb into the vicinity of the target after which the current control, through feedforward processes, would take over. Discontinuities in movement trajectory can be seen in this phase that are presumed to be the result of visual and other forms of information feedback to correct for error in the task.

Expansions of this model have been created over the years (e.g. Keele, 1968; Beggs & Howarth, 1970), the most influential of which was iterative correction model proposed by Keele in 1968. The iterative correction model, similar to Woodworth's two-component model, proposed that each movement was made up of multiple submovements (i.e. corrections) that lasted a predetermined amount of time (~200 ms). A central feature of this model is the notion of a motor program that controls the individual submovement. Each submovement is the result of feedback, both kinesthetic and visual, about limb location relative to the target. When given the appropriate amount of time, information about the environment is sampled and stored for the purpose of creating a new motor program and subsequent error correcting movement. From their work, Keele and Posner (1968) were able to determine visual processing times ranging from 190 to 260 ms, which were much more consistent with simple reaction times than were early estimates of minimal visual processing times that were approximately 400 ms (Woodworth, 1899; Vince, 1948).

In the early models of how vision mediates movement (Woodworth, 1899; Keele & Posner, 1968) it was assumed that if the movement trajectory was influenced by vision, the information was picked up at the start of the trial. This implies that any corrective submovements must be nearly completed before visual information can facilitate further error correction and aid movement accuracy (Keele, 1968). For this reason vision has often been manipulated upon initiation of movement, though some studies identified the moment when visual information became available to the subject (Carlton, 1981).

Shielding the initial portion of the hand trajectory, Carlton (1981) was able to determine the time between when the hand became visible and when the first error correction occurred as determined by the response kinematics. These visual processing times were estimated by Carlton (1981) to be around 121ms. Elliot et al. (1992) showed that when the instruction was to move as fast as possible the number of changes in acceleration were the same in all vision conditions. Interestingly, there were a greater number of corrective movements, when the instruction was to move as accurately as possible, in the visual occlusion condition than there were in the full vision condition. This led Elliott and colleagues (1992) to propose that, while vision facilitates movement accuracy, the number, or amount of corrective movements, is not mediated by the presence or absence of vision. In contrast to this more continuous model of visual control, it was suggested that vision might provide the basis for many overlapping discrete movements giving the appearance of continuous movement (Elliott, 1992/2004).

Additional models have been proposed to explain the relation of end-point variability to movement time (Beggs & Howarth, 1970; Schmidt et al., 1979; Craik, 1947). Fundamental to all of these models however has been the interest in the role of vision on movement accuracy. Elliot and Madalena (1987) focused on the ability of an individual to produce accurate purposeful movement during activities of daily living, while direct contact of visual information may not be constant, or continuous. From this perspective the assumption that any increase in spatial accuracy was a result of visual information picked up at the initiation of the movement does not account for movement accuracy in occurring absence of vision (Thomas, 1983; Elliot, 1992). Research by Elliot in the late 1980's proposed that there is a visual representation of the external environment, which begins to decay after 2 s (Elliot & Madalena, 1987). It seems reasonable to assume that goal-directed movement consists of two phases (see Elliott, 2010). The initial phase is not as ballistic as initially proposed, and online feedback appears to play a large role in grading the initial dynamic response related to the planned feedforward efferent information (Elliott et al., 2004; Elliot, 2010). This early correction, often quantified as a reduction in variance in distance between peak velocity and termination of the primary submovement, can be observed in the absence of discontinuities. This implies a more continuous, or pseudocontinuous, initial form of control, while late regulation relies more on comparison of limb position relative to the target.

Visual Information in Isometric Control

The study of vision in motor control processes is not limited, however, to simple aiming tasks. Advances in technology over the past few decades have made manual tracking in an isometric force production task a useful experimental protocol (Slifkin et al., 1999/2000; Miall, 1993; Hong et al., 2008). The use of computers, and the isometric force paradigm provides a reliable means to study a wide range of sensorimotor functions, most notably the influence of vision (Slifkin & Newell, 2000; Sosnoff et al., 2005; Vaillancourt et al., 2006).

Regulation of isometric force produces a noticeably discontinuous force trace (Slifkin et al., 2000; Kelvin et al., 2002). Irregularity in force output, consequently, is a positive property of the human motor system, as increases in force complexity result in greater ability to accurately produce an isometric force (Newell, 2002). Slifkin and

Newell in 1999 posited that this irregularity is representative of information in the system, indexed by the information transfer (Mean / Standard Deviation) and structure of the force signal in the time domain, measured by approximate entropy (Pincus, 1991).

The ability to perceive and utilize information in the environment becomes paramount to improving performance. As such, a measure of interest when studying isometric control is the manipulation of visual gain (Newell & McDonald, 1994; Beuter et al., 1995; Hong et al., 2008). Gain is the spatial scaling of force displayed on the computer monitor, known as pixel/Newton ratio. In other words, it is number of pixels lit per Newton of force applied to the load cell. Generally, the effect of scaling the visual magnification has shown a U-shaped trend related to motor performance (Newell & McDonald, 1994; Sosnoff et al., 2006). That is, as gain is increased motor performance is improved up to a certain point, at which time the performer is no longer aided by visual scaling and performance begins to decrease. Emphasis when studying error detection has been given to the visual scaling component in visual perception. Though, visual angle has been shown to be a mediator in visual perception of gain, and have an effect on variance in force output in isometric tasks (Vaillancourt et al., 2006).

Understanding the role vision plays on isometric control is important as accurate control is typically impossible when mediated by only haptic and proprioceptive mechanisms (Vaillencourt & Russell, 2002). Visual gain can increase or decrease the detection of error, which is an indication of the capacity of the human system to perceive visual information in the environment.

Hong and Newell (2008) produced a novel way of examining the effect of gain, by comparing a constant scaling parameter across all force levels, as well as setting the gain proportional to the force level. It was shown that the effective use of constant gain is negated with increase in force level as the variability grows as a function of force level, essentially making error detection more difficult. However, setting the visual gain relative to the task demands (i.e. proportional to force level) can cause periods where force is not seen on the screen, creating an inadvertent effect of intermittent feedback. The main findings of this study were that while trends in magnitude of force variability remain consistent with past work, and are seemingly inherent to the neuromuscular system, the time-dependent structure of force variability is highly related to the presence or absence of visual information. Isometric tracking tasks are ideal for exploring the relationship between intermittent and continuous control in human movement (Craik, 1947; Elliot, 1990; Miall, 1993; Slifkin et al., 2000; Elliot, 2010).

Intermittent Feedback and the Control of Isometric Force.

The intermittent nature of visual processing is well documented in discrete movements (see review by Carlton, 1992), though not as well studied in isometric tracking tasks (Slifkin et al., 2000). Craik (1947) was one of the first to state that humans in a manual tracking task behave like an intermittent servo, suggesting that all corrective movements within a tracking task are ballistic in nature and operate with a defined time period of about 200 ms. This set lag time, determined by experiments on simple reaction time (Donders, 1869), was attributed to the refractory periods in nerve conductance and the time needed to send signals from the site where the sense organ was first activated. These views on manual tracking, though not specifically referring to isometric force, are not so dissimilar from the two-component (Woodworth, 1899) and iterative correction (Keele and Posner 1968) models discussed earlier.

One of the lesser-studied forms of manipulating visual feedback is the intermittency or frequency of feedback providing information for the performer of the error between their movement output and the target (Silfkin & Newell, 2000; Sosnoff et al., 2005). Since Craik (1947), strong evidence has been provided for the ability of the performer to make corrections at periods shorter than 200 ms (Zelaznik, 1983; Slatter-Hammel, 1960; Whiting et al., 1970; Beggs & Howarth, 1970; Slifkin & Newell, 2000; Sosnoff & Newell, 2005; Hong, 2008). Advances in modern computer technology have allowed isometric force tracking to become an ideal means for measuring intermittent visual processing, because of the ability to precisely manipulate time intervals between successive visual feedback presentations, or feedback frequency, as well as giving behavioral and physiological measures in both time and frequency domains about the structure of the force output. Additionally, using index finger abduction in this isometric tracking paradigm should be less complicated than tracking a varying waveform, or a manual aiming task where both hand and target potentially could move, due to the reduced biomechanical degrees of freedom (Slifkin et al., 2000).

Slifkin et al. (2000) investigated the effect of intermittent visual information on the force output control by manipulating the time between presentation of feedback points (intermittency) about a subjects force trace in an isometric tracking task. Feedback frequency was intermittently varied at a low rate of .2Hz (~5sec), up to a high of 25.6Hz (40ms). They tested the idea that the human system would be able to utilize all incoming information, specified by a 1:1 regression equation, and whether frequency in force control were amenable to fast feedback frequencies. The findings showed that the ability to utilize increases in information, as indexed by task performance, departed greatly from a 1:1 relationship, and changes in performance were described by a hyperbolic curve as the time intervals between presentation of visual information decreased. This improvement tended to increase until the 6.4Hz (~150ms) condition, after which any further improvement was negligible. One of the aims of the study was to test the hypothesis that increases in feedback frequency should entrain correlated shifts in power to higher frequencies in force output, however no supporting evidence was found, and performance was almost exclusively mediated by reductions in spectral power at about the 1 Hz bandwidth. The discontinuity between visual (150ms) and motor (1Hz) modulations led Slifkin et al. to propose a model of isometric force control where visual information is sampled at about 150ms (6.4Hz) and a subsequent motor correction occurs every second (1Hz).

The idea that during periods of correction visually sampled information is stored and superimposed for the purpose of creating a subsequent error correction is inline with past work (Keele, 1968; Elliot, 1990), but there are subtle theoretical issues with this model. Firstly, results were based on an experimental design that examined only one force level (40% maximal voluntary contraction), when it has been shown in the past that both frequency and time dependent structure of force output is mediated nonlinearly with the level of force output (Slifkin & Newell, 1999, 2000). Secondly, it seems counter intuitive that movement corrections can only occur every second when it has been well established that movement corrections can occur on a much faster time scale (Smith & Bowen, 1980; Zelaznik, 1983; Miall, 1993; Sosnoff et al., 2005). Interestingly not well acknowledged in the conclusions of this work was that each of the dependent variables were mediated up to a different time interval. Breakpoint values, or the point at which further visual information no longer facilitated improvement in the variable of interest, ranged from 5.06Hz (193ms) for mean force level and 10.62 Hz (94ms) for power spectrum exponents. Even though this range is consistent with previously reported values in discrete movements (Carlton, 1992), this discrepancy in breakpoint values, and further lack of consistency between group mean and individual averaged data suggest different properties of control may not effected by vision equally.

Interested in attempting to resolve some of these issues, as well as explore this issue of periodic control further, Sosnoff and colleagues (2005, 2006), in a series of studies sought to examine the multiple time scales of continuous force control. Addressing a dependency of information transmission on force level, it was predicted that the amount of visual information needed to improve performance would be influenced by force output level. Using 4 distinct force levels (5%, 10%, 25%, 50% MVC), the primary finding of this study was that the level of intermittent visual information interacts with force level to modulate the strength of the long-range correlation in the frequency structure of the fore output. Additionally evidence was provided against the notion that there is a modal frequency, as significant effects were found to modulate frequency up to 12Hz as intermittency decreased, though only in the 10% and 25% force level conditions. It was posited that isometric control should not be characterized by its minimal visual processing speed. Visual-motor processing is dynamic in nature, composed of multiple timescales of control that incorporate both feedback and feedforward process that vary with demands of the task (Sosnoff et al., 2005). The frequency, and/or speed at which the task is performed has been shown to influence the minimal visual processing time, where movements produced greater than 2 Hz do not show improvement in task performance with more finely grained information (Sosnoff, Vaillancourt, & Newell, 2004; Sosnoff et al., 2005; Pew, 1974).

Shortly after this initial follow up study, Sosnoff et al. (2005, 2006) were able to further parse out the differences between multiple processes the human system related to variance of force output and dependencies of task performance in both time and frequency domain. Attempting to move away from a theoretically simple control mechanism of index finger abduction, Sosnoff et al. (2005) examined the periodic informational effects on coordinated force output from two and three digit grip configurations. The ability to increase control of individual fingers increases significantly with increases in information presentation, but as availability of information is decreased the CNS adapts to the currently imposed constraints and switches to more of a feedforward control mechanism, further entraining the coordinated fingers (Hong, 2008). It was proposed that the ability to improve coordination between fingers is dependant of the amount of visual information present (Sosnoff et al., 2005). Apparent from the bulk of this work is the interaction between seemingly individual control processes, as well as suggesting an inherent capacity of the human system to adapt to a multitude of task constraints (Hong & Newell, 2008).

Focus of Thesis

The aim of the current investigation is to re-examine the trends in the multiple-timescales of control influencing the structure of force output as mediated by force level previously (Sosnoff & Newell, 2005; Slifkin & Newell, 2000), as well as provide further evidence for the interaction between intermittent visual feedback and force level of isometric finger force production. Past studies (Slifkin & Newell, 1999) examined a broad range of force levels, however near maximal force targets have been shied away from in subsequent studies (Sosnoff et al., 2005) with the upper limits around 45%-50% of the maximal voluntary contraction (MVC). Neglect of the upper force levels is mostly due the potential inducing fatigue and the inability of the subject to maintain an accurate force output.

In the current investigation we manipulated 3 force levels (15%, 30%, 60% MVC) of an inverted-U shaped trend of the dependent variables presented by Slifkin and Newell (1999). As way to further exploit the adaptive nature of the individual, 3 different hand conditions (right, left, dual) were used to explore any differences in multiple control processes discussed here. The general hypothesis tested was that the frequency of intermittent feedback will interact with force level to influence the structure of force variability. It is predicted that the amount of discontinuous visual information able to be utilized by an individual will be influenced by the relative force level imposed by the tracking task, as well as the adaptability of visual control to be dependent on the additional of biomechanical degrees of freedom as part of the coordinated force output between the two hands.

Additionally, the design of the study afforded examination of the differences in motor output between the right and left though the direct interpretation of hand dominance was not the main focus of this thesis. Analysis of right and left hand difference has lead to the suggestion that the dominant limb is more adept at using predictive mechanisms to utilize dynamic information from the limb, whereas the non-dominant limb optimizes the stability around a set point position (Sainburg, 2010; Mutha et al., 2013). This hypothesis is indirectly tested in the current study by contrasting the left and right handed performance of right handed participants in single and dual limb isometric force protocols.

CHAPTER 2. VISUAL INFORMATION AND THE MULTIPLE TIMESCALES OF ISOMETRIC FORCE CONTROL

Introduction

Intermittent visual feedback has shown to have an effect on the time and frequency structure of force output (Slifkin, 2000; Sosnoff et al., 2005, 2006). Furthermore, inferences regarding visual processing in continuous force production have revealed multiple timescales of isometric control. It appears that processing capacity is influenced by given task constraints. It is suggested that time-dependant properties of force control are a result of an interaction between visual information and force demands, while force variance (i.e. SD) is an inherent property of the motor system (Hong et al., 2008). To further examine these issues, force level and frequency of visual feedback were manipulated to determine the nature of their influence on the multiple timescales of isometric force control.

Methods

Participants

There were 15 participants with a mean age of 25.1 years old (±4.25 years) from The Pennsylvania State University who participated as volunteers in the experiment. Six of the participants were female, and none had a previous history of neurological disorder. All participants were right handed. Hand dominance was determined by self report. Informed consent was obtained from all participants consistent with the approved IRB of The Pennsylvania State University.

Apparatus

Subjects sat in a chair approximately 60cm (23in) in front of a 23in LCD monitor. Immediately in front of the monitor were two Entran ELFS-B3 load cells that were mounted vertically on separate wooden blocks, spaced approximately 7.5 inches apart, and used to record the data during experimental trials. During an experimental trial, force output from one or both of the load cells, depending on the testing condition, was amplified and then sampled at 120Hz by a 16-bit Coulbourn A/D board. The isometric program was coded using C++ software.

No physical constraints were used during testing procedures, however, subjects were instructed to keep their palm, wrist, forearm and elbow flat against the table in the most comfortable position. Participants were asked to maintain this same arm configuration throughout the testing period. Participants were able to view their force output on a 23in Acer computer monitor with a resolution of 1920 horizontal pixels and 1080 vertical pixels. The pixel-to-Newton ratio was set at 64 p/N, meaning for every Newton of force applied to the load cell 64 pixels were illuminated, providing feedback about the subjects force trace.

Procedures

Before testing procedures commenced, participants were given a familiarization block, in which subjects used both right and left hands individually, and were also given the chance to use both together (dual condition). Upon completion of the familiarization trial block each subjects maximal voluntary contraction (MVC) was collected. By way of abducting their index finger, pressing with the lateral aspect of the distal phalange, subjects were asked to produce the maximum amount of force possible for a 6 s trial. This procedure was repeated 3 times, with a 20 s break in between each trial, and the average of the 3 trials was defined as the MVC for that hand. The average was taken as opposed to the maximal force achieved to account for any decrease in maximal attainable force as testing progressed. To account for any effects of bilateral force deficit, MVC was collected for each hand condition at the start of the condition. It has been shown that as two limbs work together in a bilateral force production task, MVC of the coordinated output will be equal to the summation of the two individual hands (Oda & Moritani, 1994). As such, here we collected separate MVC's for the right hand, the left hand, and from the total output of the dual handed condition.

Testing conditions were pseudo randomized. Intermittency values were randomized within each target force level (15%, 30%, or 60%MVC), while force levels were randomized within in hand type (right, left, or dual), and each hand condition was randomized for each participant. Similar to Slifkin and Newell (2000) subjects were asked to produce isometric force to match a red target line that was displayed on the monitor. Feedback frequency about the subject's force trace was intermittently occluded and defined as the number of pixels lit per second. Force output was displayed on the monitor as illuminated pixels perceived as yellow dots providing spatial-temporal representation of the subjects force-time series for given moment.

Six intermittency values were used at .8, 1.6, 3.2, 6.4, 12.8, and 25.6Hz. The lowest feedback frequency, or largest time interval separating illuminated pixels was 1,250ms (.8Hz) and the largest frequency or smallest time interval was set at 40ms

(25.6Hz). For example, in the largest intermittency condition (.8Hz), exactly 1,250ms after the start of the trial a single feedback point would be displayed, representing the participant's force trajectory at that moment in time. No further feedback would be given until the second time interval (1,250ms) had elapsed. This process would continue on until the end of the trial. So, as feedback frequency increased from .8 to 25.6Hz for a given trial, the time period between illuminated pixels representing the subjects force trace decreased, effectively increasing the information each participant received about their force output.

At the start of testing and after the familiarization period participants started testing conditions either with their right hand, left hand, or both hands together (dual). For example, if subjects were using their left hand, they would have a block of 3 trials per intermittency value for a total of 18 trials per force level (56 trials per hand condition). All trials at a particular force level were completed before moving on to the next target level. Once all trials were completed in each force level, testing for that specific hand condition was finished, and the same processes were repeated for each of the remaining hand types (i.e. right hand and dual conditions).

During all trials subjects were instructed to minimize the deviations between their own force output (illuminated pixels) and the red target line as much as possible. The root mean squared error (RMSE) was presented to the subject on screen, after the completion of the trial to provide knowledge of results. Using the final 10 s of the trial, RMSE was calculated with $[\Sigma(s_i – f_i)^2/n – 1]^{1/2}$, where s_i is the ith value of the target, f_i is the ith force sample, and n is the number of data samples.

Data Analysis

The first 4 s and last 1 s of each force-time series were omitted from all analyses. The initial 4 s were omitted in order to ensure that the time series did not include the period over which force was being adjusted and stabilized, and the final 1 s was omitted to help account for transient effects of fatigue that may have accumulated during the trial. All data were analyzed using MatLab 8.1 (Mathworks, 2013).

The descriptive statistics used here to evaluate task performance were constant error and standard deviation of the force output. The mean and standard deviation (SD) provide information about the ability of the performer to produce the required task output as a function of the feedback frequency (intermittency). Constant error (CE) was used to determine how accurate on average the mean output for an individual trial was to the target level. A mean force that exactly matched the target force level would provide a measure equal to zero.

Structure of force output was also assessed in both time and frequency domains. Approximate entropy (Pincus, 1991), used here to determine the dynamics in the time domain, returns a measure of the stochasticity of the force output. This measurement represents the predictability of future values in the time series. This is done by defining a template length (m) and noise amplitude (r) to compare a time series of length (N) data points. Number of data points ('N') used for the analysis of ApEn was 1200, while 'm' is set to 2, and 'r' is set to .2SD. A lower value approaching zero would indicate a perfectly regular signal, such as a sine wave, whereas a value approaching two would suggest a signal that much more irregular in time, much like Gaussian white noise.

The power spectrum was computed using the power spectral density function in MatLab v. 8.1(MatLab, 2013) that uses Welch's averaged periodogram method. A 256-point nonoverlapping Hannning window was used, with a sampling frequency of 120Hz, resulting in a 0.47 Hz binwidth. To examine how power changes as a function of intermittency and force level, the amount of power was divided into bandwidths of 0-4Hz, 4-8Hz, and 8-12Hz. Separately, a power function was fitted to the spectral profile in the form of $P = \alpha(f^\beta)$. Where, β, is the power function exponent which scales changes in spectral frequency to spectral power, from which spectral slope or rate of change can be determined. As the power spectrum becomes more broadband (i.e. resembles Gaussian white noise) values of β will increase from negative values towards zero.

All dependent variables of interest were submitted to a three-way (3 X 3 X 6) repeated measures ANOVA with hand type (i.e. left, right, dual), force level (15%, 30%, 60% MVC), and intermittency (.8 Hz, 1.6 Hz, 3.2 Hz, 6.4 Hz, 12.8 Hz, 25.6 Hz), as the factors. A separate general linear model was run to compare the effects of the contributions from the right and left hands to the combined total output in the dual condition. The Bonferroni correction was used to compare the specific effects contributing to the general ANOVA. All statistics were deemed to be significant when there was less than a 5% chance of making a Type 1 error ($p < 0.05$). All statistical analyses were performed using IBM SPSS software.

Results

Task Performance

Figure 1 shows the constant error of the force output as a function of intermittency for the left and right hands and the dual condition. Constant error had a main effect of force level, $F(1.2, 16.7) = 20.2$, $p < 0.001$, while there was no effect of hand ($p = .330$, $\eta^2 = .075$) or intermittency ($p = .771$, $\eta^2 = .016$) on the ability to match the force target line. The three-way interaction between hand, force level, and visual intermittency was not significant ($p = .122$, h2 = .091). Any interaction between hand conditions and intermittency did not reach significance ($p = .52$, $\eta^2 = .170$) after applying the Greenhouse-Geisser correction to account for violations of sphericity, $X^2(54) = 163.134$, $p = 0.00$.

Post hoc analysis revealed that the 60%MVC force level was significantly different from the 15% and 30% MVC conditions. This result was present for both hands, and the dual conditions, indicating that regardless of intermittency rate, subjects were able to match the target force requirement. Typically, the 15%MVC over shot the target, and error of each of the larger force levels became increasingly more negative relative to the target.

Figure 2 shows SD decreasing in a negatively accelerating fashion as a function of intermittency level. There was a main effect of force level on the variance (SD) of force output, $F(2, 28) = 31.465$, $p < 0.001$. Additionally, there was an effect of visual intermittency, $F(2.27, 31.87) = 13.106$, $p < 0.001$, and hand type (i.e. Right vs. Left vs. Dual), $F(1.23, 17.32) = 6.37$, $p < 0.05$, on the SD of force output. Two-way interaction between force level and feedback frequency did not reach traditional levels of statistical significance ($p = .137$, $\eta^2 = .098$).

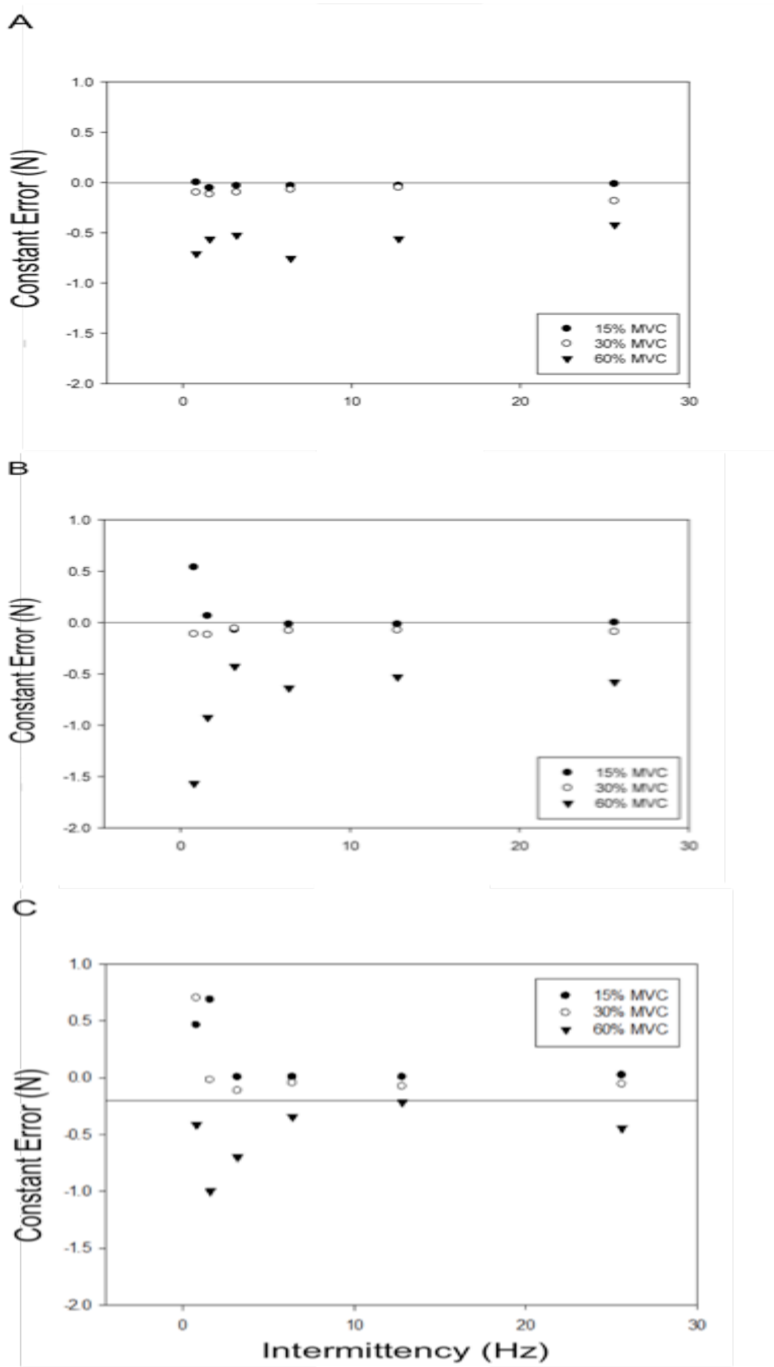

Figure 1. (A) Changes in constant error of the mean force output from the left hand relative to the force target. (B) Changes in constant error of the mean force output from the right hand relative to the force target. (C) Changes in constant error of the mean force output from the dual handed condition relative to the force target.

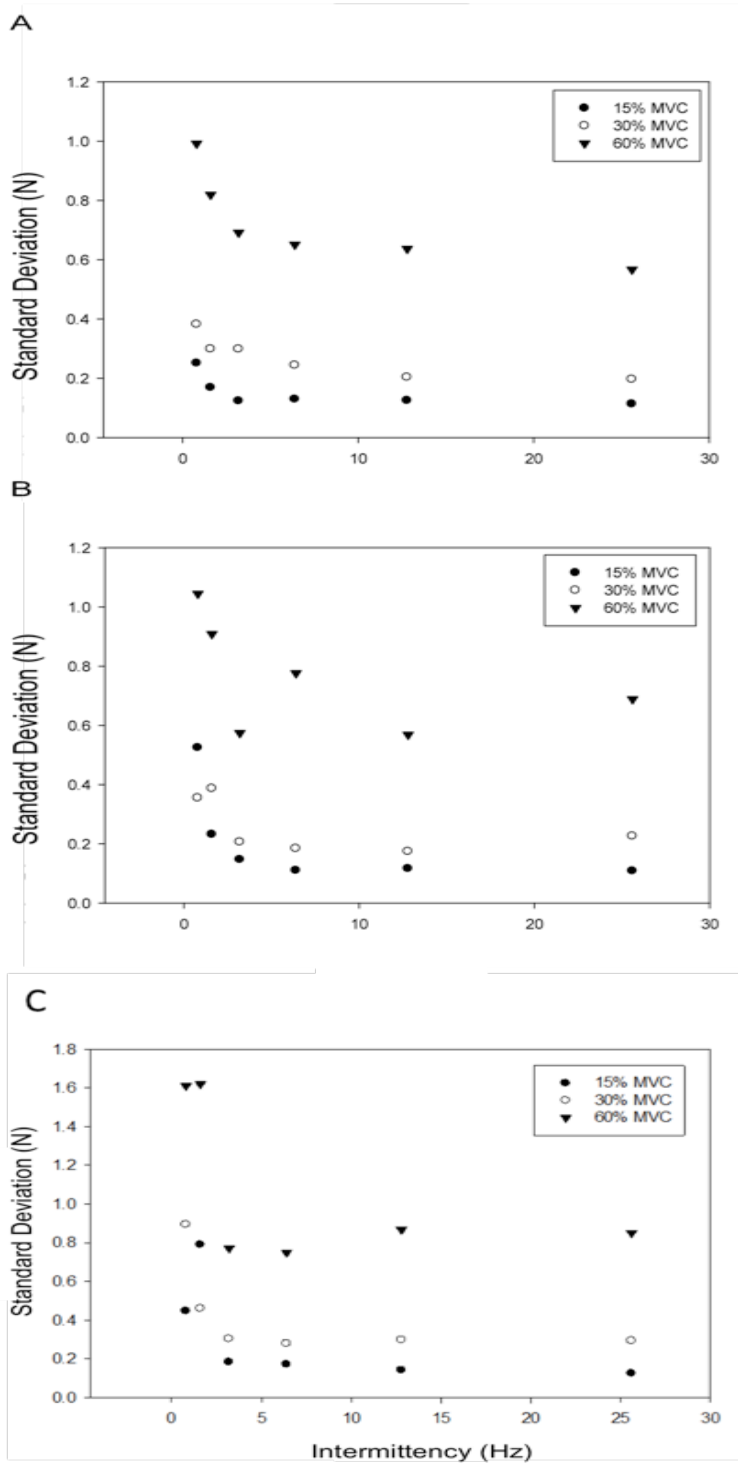

Figure 2. (A) Standard Deviation of the force output from the left hand as a function of intermittency. (B) Standard Deviation of the force output from the right hand as a function of intermittency. (C) Standard Deviation of force output from the dual handed condition as a function of intermittency

Post hoc analyses showed significant differences between intermittency levels as visual presentation rates increased. Even though there was a visible negatively accelerating trend in the data, only feedback rates up to 3.2 Hz were significantly different from the higher feedback frequencies. This corresponds to time of 312.5 ms between visual feedback points. Comparison of the main effect of force level showed only the 60%MVC force level was significant.

Given the inherent differences between the single handed and dual handed conditions, SD of the coordinated output from the combined effort of both right and left hands was explored further. Again, there were effects of force level, $F(2, 28) = 27.98$, $p < 0.001$, and intermittency, $F(2.2, 30.7) = 5.34$, $p < 0.001$, however there was no effect of each hand on the variance of the total output ($p = .608$, $\eta^2 = .019$). Post hoc examination of the effect of force level on the standard deviation showed that differences were only significant at the 60%MVC condition. Important to note, however, is that an this two-way interaction between visual information and force level did not reach traditional levels of significance ($p = .467$, $\eta^2 = .054$).

Figure 3 shows the contrast between the standard deviations from each finger's relative contributions to the coordinated output. Reductions in SD due to increasing visual presentation rate seems to have an effect up to 3.2 Hz at the 15% and 60%MVC force levels, while variance at 30% force output showed significant effects of intermittency up to 6.4 Hz.

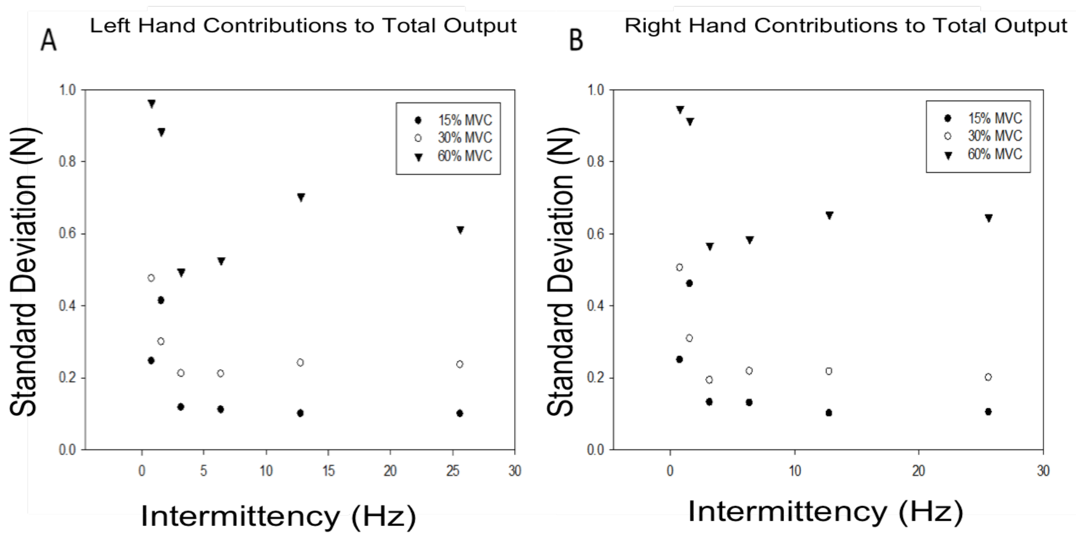

Figure 3. Contributions from the individual hands to the total output from the dual handed condition. (A) Standard deviation from the left finger output. (B) Standard deviation from the right finger output.

Structure of Force Output

The analysis of ApEn showed that irregularity of the force output increased as a function of increasing intermittency, $F(5, 70) = 94.53$, $p < 0.001$. Conversely, the predictability, or regularity, of the force output increased as a function of force level, $F(2, 28) = 1.261$, $p < .001$. Post hoc comparisons revealed that there were statistically significant differences between feedback frequency values at each force level, $F(10, 140) = 2.335$, $p < 0.05$. The lower force levels were able to better use the greater availability of visual information (i.e. increases in the irregularity), with significant differences in the structure of the force output up to 6.4 Hz of visual feedback presentation. At the highest criteria force level (60% MVC) enhancements in complexity was significant only at the slowest intermittency rates (.8 Hz – 1.6 Hz).

Spectral slope provided further support for the influence of intermittency on the structure of force output. Spectral slope is an index that shows how broad the force spectrum is. Values that approach 0 are broader and resemble more closely Gaussian white noise.

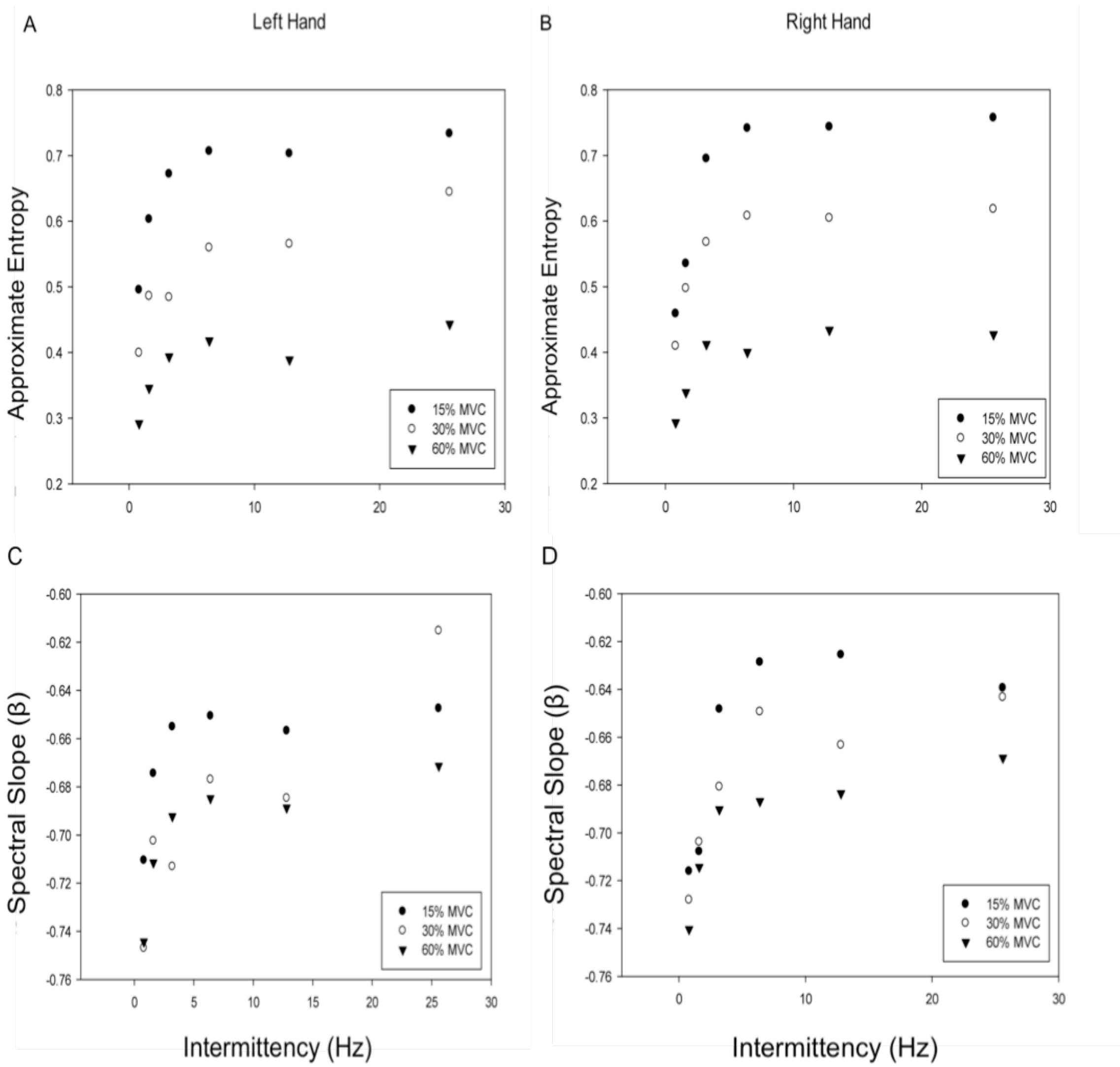

Figure 4. (A) Approximate entropy of the left hand as function of intermittency. (B) Approximate entropy of the right hand as a function of intermittency. (C) Spectral slope of the left hand as a function of intermittency. (D) Spectral slope of the right hand as a function of intermittency.

Figure 4 shows a comparison of ApEn and spectral slope between the right and left hands. The effect force level had on the spectral slope did not reach traditional levels of significance ($p = .088$, $\eta^2 = .187$). There was a significant effect of the rate of visual feedback on the force spectrum, showing a broadening as intermittency was reduced, F(3,

42) = 56.765, $p < 0.001$, up to 6.4 Hz. Interestingly, all other within subject effects, hand ($p = .314$, $\eta^2 = .076$), hand x force ($p = .768$, $\eta^2 = .022$), hand x intermittency ($p = .337$, $\eta^2 = .077$), force x intermittency ($p = .116$, $\eta^2 = .127$), and hand x force x intermittency ($p = .239$, $\eta^2 = .080$) were all found non-significant.

Figure 5 shows a comparison between the time dependent structure and spectral slope of the coordinated force output. Each hand in the dual condition was significantly effected by force level, $F(2, 28) = 33.413$, $p < 0.001$, and intermittency, $F(5, 70) = 16.815$, $p < 0.001$. Likewise, only intermittency was found to have an effect on the broadband structure of the contribution of each hand to the total output, $F(2, 31) = 24.335$, $p < 0.001$. Decreasing temporal delay between visual feedback points, representative of the force pattern, was found to have a significant effect at intermittency rates of approximately 150 ms (6.4 Hz).

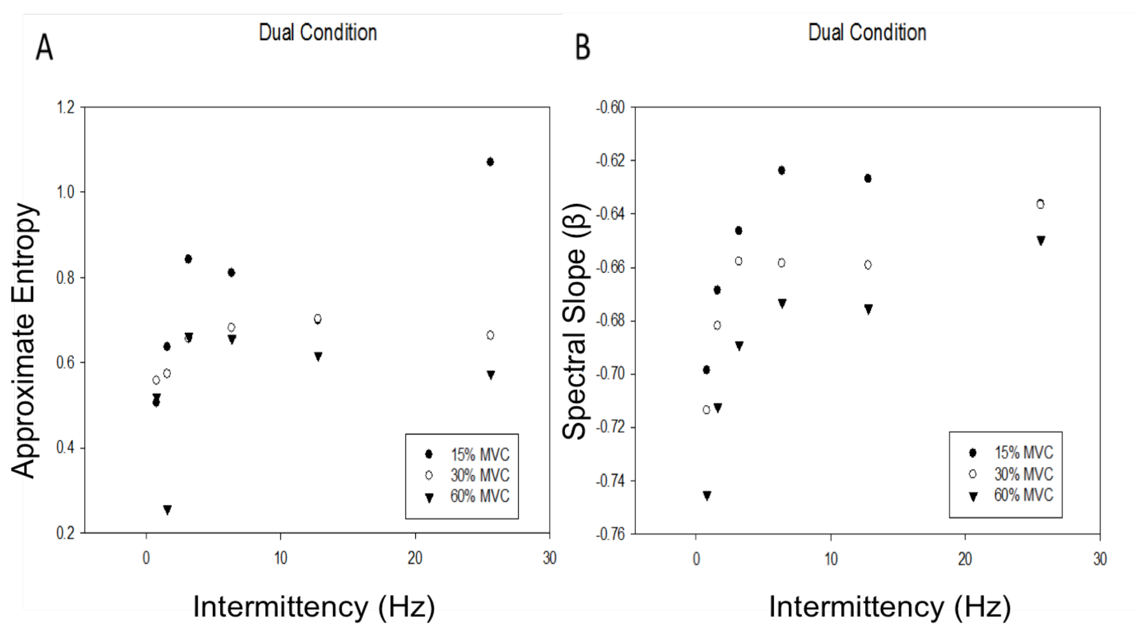

Figure 5. (A) ApEn score from the total force output in the dual handed condition as a function intermittency across all force levels. (B) Changes in spectral slope as a function of intermittency across all force levels in the dual handed condition.

Power Spectral Bandwidth Analysis

When plotted, exponents from the power function provide information about the changes in the power spectrum as a function of decreasing intermittency rates. To gain further evidence of the effect of visual information on the frequency of force output the power spectrum was partitioned into frequency bandwidths ranging from 0 - 4 Hz to 8 – 12 Hz. Figure 6 shows the change in power at each force level as time between visual feedback is decreased. As expected there were main effects of force level and intermittency on the spectral power. In right handed conditions there was significant 3-way interaction between bandwidth x force level x intermittency, $F(20, 280) = 1.756$, $p < 0.05$. This 3 way interaction failed to reach significance in the left handed conditions, ($p = .160$, $\eta^2 = .103$), although, the bandwidth x force interaction, $F(2, 22) = 9.857$, $p < 0.001$, as well as the bandwidth x intermittency interaction, $F(4, 55) = 9.788$, $p < 0.01$, were significant.

Post hoc analysis of the 3-way interaction in the right hand revealed lower levels of motor output were able to use more fine-grained amounts of visual information (6.4 Hz) across all bandwidths. There were less noticeable trends at the intermediate force level within each bandwidth. At the 0 – 4 Hz bandwidth only the 6.4 Hz intermittency value was significant, while only feedback frequencies of 6.4 Hz and 25.6 Hz in the 4 – 8 Hz bandwidth reached significance. No intermittency value with in 8 – 12 Hz frequency was statistically significant. The 60% MVC force level showed no significant differences in power at any bandwidth.

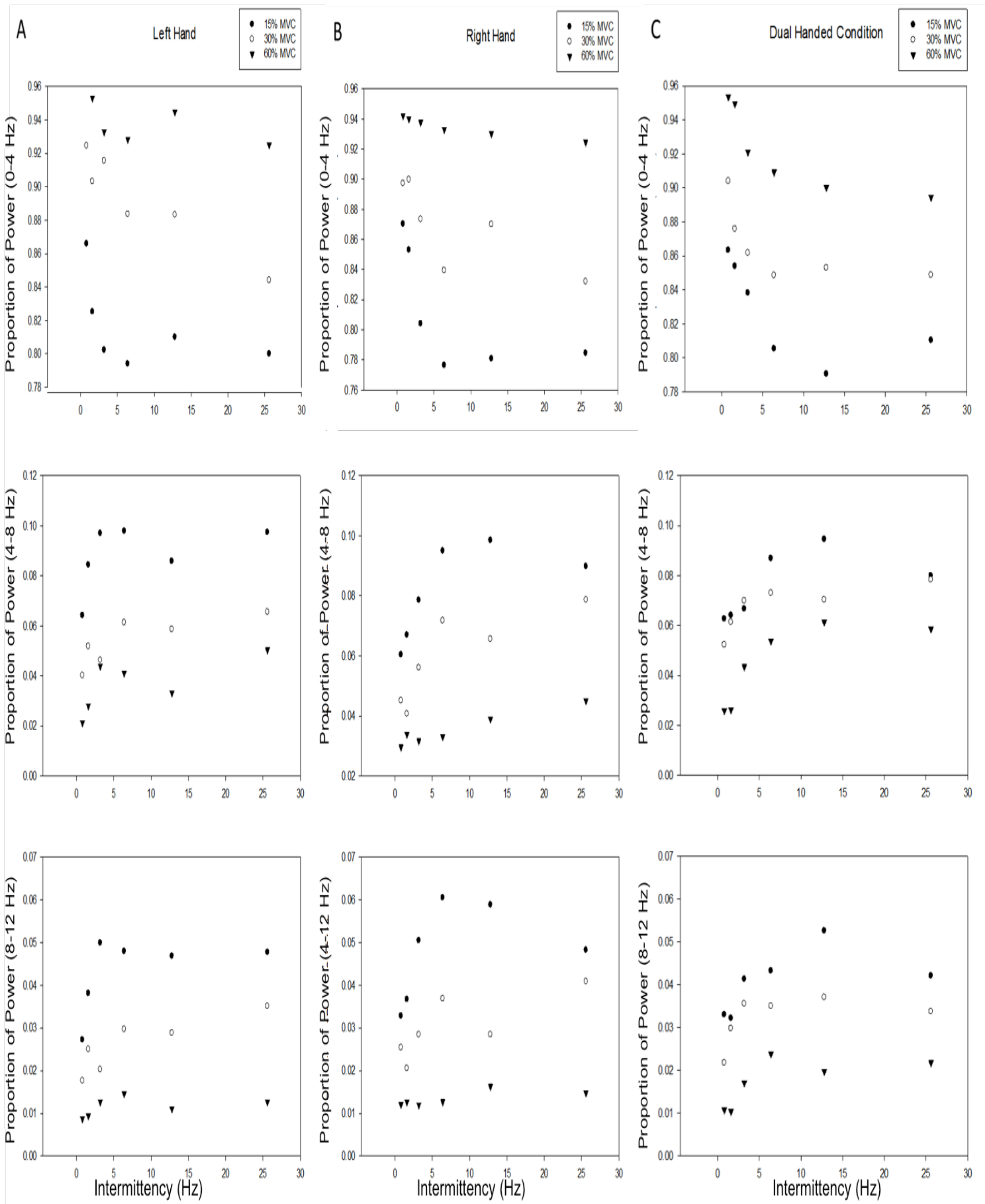

Figure 6. (A) Changes in the proportion of power in the 0 – 4, 4 – 8, 8 – 12 Hz frequency bandwidths as a function of intermittency at each force level produced by the left hand. (B) Changes in the proportion of power in the 0 – 4, 4 – 8, 8 – 12 Hz frequency bandwidth as a function of intermittency at each force level produced by the right hand. (C) Changes in the proportion of power in the 0 – 4, 4 – 8, 8 – 12 Hz frequency bandwidth as a function of intermittency at each force level produced by the dual handed condition hand.

Post hoc analysis of the power density from the left hand showed similar changes as the right. Significant changes in power in the 0 – 4 Hz bandwidth were only in the force magnitude requirement. Despite noticeable increases over the largest intermittency values, changes in power in the 4 – 8 Hz bandwidth were not significant across all force levels. Increases in power of the fastest frequency components were significant at all force levels. Examination of the bandwidth x intermittency interaction revealed significant differences between feedback frequency values only at the slowest presentation rates (.8 Hz – 1.6 Hz) across all bandwidths.

Similar to the right and left hands considered separately, the combined force output from the dual condition showed significant interactions between bandwidth x force, $F(1, 18) = 10.03$, $p < 0.01$, and bandwidth x intermittency, $F(4, 52) = 10.208$, $p < 0.001$. Changes in proportion of power with in the individual frequency bandwidths significant only at the 60% MVC condition. Post hoc comparisons of the effect of intermittency on the proportion of power showed that the 0 – 8 Hz bandwidth range influenced by vision with increasing rates of feedback up to approximately 150 ms.

CHAPTER 3. DISCUSSION

This experiment investigated the relation of task constraints on the ability of the performer to perceive and use available information to improve isometric force control. How the intermittent nature of vision influences control processes has been a focus of researchers for over a century. Recent models suggest the initial phase of Woodworth's (1899) two-component model is not as ballistic as originally proposed (see review by Elliot, 2010), and the line between discrete versus continuous visual control may not be as definitive as described in past work (Craik, 1947; Keele, 1968; Schmidt, 1970). Findings of the current experiment are in-line with these more recent views on visual-motor control (Elliot et al., 2004, 2010), and provide support that there are both stochastic and deterministic timescales of isometric force control.

Evidence of this is demonstrated by the concurrent increase of the force timescale irregularity (ApEn) as variability (SD) is reduced as a function of faster visual feedback frequencies. Furthermore, we found support for the postulation that task performance variability (SD) is independent of the temporal structure of visual feedback, indicating it is an inherent feature of the musculoskeletal system (Hong et al., 2007, 2008). The ability to accurately maintain an isometric force is greatly dependent on the intermittency of visual information, and further influenced by the amplitude of motor output.

Influence of Visual Information in Isometric Force Variability

Magnitude of force variance was increasingly influenced by the amplitude requirements at the higher force levels. Despite variance being scaled to the relative force targets, subjects were consistently able to produce force with vary little constant error above or below the target. It was only when attempting to produce force at the highest target level that subjects were unable to match the target force accurately, and ended up undershooting the prescribed force. Interestingly, at the lowest force level (15% MVC) and with inadequate amounts of visual information subjects consistently, over shot the target, while at the midrange force level they were able to match the target almost exactly. Even with significant differences at the 60% MVC condition, the largest deviation only occurred at the lowest visual presentation rate (1250 ms). With appropriate visual information the constant error was not excessive, and only around .5 N below the target. Analysis of the constant error indicates the ability of the subjects to match force targets across a wide range of intermittency values.

There was little interaction of feedback frequency in the visual intermittency conditions, with greatest effects coming when temporal delays in visual presentation were approximately 1250 ms (.8 Hz). The magnitude of force did not have a significant influence on the ability to utilize more fine-grained information with respect to matching a force target. Any reduction in constant error as a function of visual temporal delay, reached a plateau at an intermittency rate of approximately 300 ms (3.2 Hz) across all force levels. Likely, this result demonstrates the degradation of a visual representation (Elliot & Madalena, 1987), and further supports the notion that in the absence of visual information beyond a certain point, haptic and proprioceptive feedback is not sufficient to maintain isometric force (Vaillancourt & Russell, 2002). This is indicative of a minimum amount of visual information needed to complement afferent information from the extremities, for the purpose of maintaining constant force (Hong, 2008).

The magnitude of force variance was reduced significantly with decreasing intermittent visual occlusion. By increasing the amount of visual information displayed on the screen subjects were better able to make necessary corrections in their deviations from the target line. Variance was scaled proportionally with force level regardless of visual information, whereas greater temporal delays in visual feedback influenced both the time and frequency structure of continuous force production.

Findings from the force variance trends here are supportive of similar findings by Hong and colleagues (2007). It was posited that the distributional properties of force variance are an inherent property of the human musculature (Hong et al., 2007, 2008). Motor output variance has been linked to the additional recruitment of available motor units (Slifkin et al., 1999). Because of the size principle (Henneman, 1957) as force requirement is increased and more large fast fatigable motor units are recruited, the more difficult it will be to accurately match the target as their may be a large discrepancy in the output of smallest to the largest motor units. Additionally the majority of available units are recruited around 50% MVC (Grillner & Udo, 1971), therefore any further increase in force production must be accomplished by the rate coding of the active units (Kamen, Sison, Du, & Patten, 1995).

Isometric force production is defined as having no changes in length, however, this assumption would seem to be invalid as studies have shown systematic trends in the magnitude and structure of force variance as a function of force level (Slifkin et al., 2000; Hong et al., 2007). The exponential increase in variance (SD) of force output found by past studies is believed to a result of force-length properties of the muscle (Hong et al., 2007). Nonmonotonic increases in force with change in muscle length show parallel changes to those found in the variance of force output. The active force-length curve shows an optimal range in the middle of possible length values. With change in muscle length, muscle force increase up to a maximal amount and any further change in length will cause a decrease in force (Gordon et al., 1966). This property of muscle along with the findings that variance follows a similar trend supports the notion that increase in force variance is a time-independent property inherent to the muscle physiology (Hong et al., 2007, 2008).

Structure and Multiple Timescales of Isometric Force Control

Examining the effects of increased visual information on the task performance of isometric control can reveal much about the mechanisms underlying the visual-motor processes. Important to know and understand is the inverse nature between force variability and visual information, yet this does not explain the relation to the physiological complexity (ApEn) of the force signal. Past work has suggested that with greater availability of visual information (i.e. reduced intermittency) there is a greater likelihood of correcting for movement errors in the force trace (Elliot et al., 1990, 2010), while not enough information will cause the performer to use more pattern generation and feedforward processes (Pew, 1974). Through analysis of ApEn, we were able to demonstrate the notion that reducing the temporal delay of visual information will have an inverse relationship to the force time series irregularity across all force levels. However, as force level was increased, we were unable to find the U-shaped trend in ApEn as reported by Slifkin et al., (1999). ApEn is generally sensitive to measurement parameters (Forrest et al., 2014) and this may account for some of the differences found in the current work to previous research (Sosnoff et al., 2005; Slifkin, 2000). Nevertheless, our findings show motor output became increasingly more probabilistic with increase in force.

Improving the visual density displayed on the monitor did allow the performer to reduce the deterministic structure of the force output, but this relation was not consistent across all force levels, as it was with performance variables. Producing force with lower amplitude requirements allowed subject to increase force complexity at faster feedback frequencies (6.4 Hz) then when asked to produce force at the highest force output target (60% MVC). Interaction between force requirement and temporal structure of visual information provides evidence indicative of the multiple timescales of force control (Mayer-Kress et al., 2003; Sosnoff et al., 2005).

Concurrent with measures of ApEn are inferences about spectral slope. As intermittency was reduced, and greater amounts of information was presented on the screen, subjects were able to improve the irregularity in the time domain of the force signal and with that comes a reduced (i.e. less negative) power scaling exponent, indicating a greater contribution from faster frequency components within the force output. Spectral slope is the inverse relationship between power and frequency within a time signal and appears to be consistent across force levels.

Even though the spectral slope shows a global index of the frequency structure of the force output, separate frequency bandwidths have shown to be differentially modulated by visual information (Baweja et al., 2010). An important finding from this study is the effect of visual intermittency on the individual frequency bandwidths at varying force levels. We found that power in the 0 – 4 Hz frequency band is reduced with increases in visual information, leading to a shift in proportional power contributions from the faster frequencies. A result of which coincides with in the decrease in the power spectral slope. This effect of intermittency, was only present in the 0 – 4 Hz bandwidth at the lower force requirements, while power across all frequency bands at the largest force amplitude frequency was uninfluenced by increased visual information. Similarly the power output form the left hand was modulated across all bandwidths with increases in visual feedback only at the lowest intermittency conditions. It is important to note that power is that subjects were better able to modulate their output at the faster frequencies with improved visual feedback across all forces, whereas the 0 – 4 Hz bandwidth was most effected at the highest force level. It is possible that this modulation of the separate bandwidths is related in part to the additional proprioceptive feedback, undoubtedly present in some minor fashion. However, by parsing the frequency structure in to three individual bandwidths it is hard to say for certain at what frequencies visual information has the largest impact.

Relatively Invariant Characteristics of Isometric Control

Across all dependent variables discussed in the current study, it is clear that there is not one process that is able to characterize isometric control even amongst different hand conditions. The variance (i.e. CE and SD) showed that while vision is likely the most vital of the sense organs for accurate control of continuous force, it is not the only one. The ability of each hand conditions to require only minimal amounts of visual information to meet task demands shows the compensatory nature and adaptive capacity of the human system (Hong et al., 2008). Trends in the dependant variables remained relatively invariant across all hand types, and while increase in biomechanical degrees of freedom can enhance the ability to use available information (Sosnoff et al., 2005), the relation between magnitude and structure shown here is relatively robust across effectors.

Comparison of these relatively invariant effects of vision on force variance (CE and SD) to the interaction between structure of force (ApEn) and visual feedback frequency further supports the notion that standard deviation is time-independent and an inherent property of the musculoskeletal system (Hong et al., 2007). Similar trends in ApEn and spectral slope with decreasing intermittency demonstrate the relationship between the time and frequency domain that is required for constant force production. These trends were all consistent across the multiple hand conditions providing strong evidence for relatively invariant visual-motor control mechanisms, mediated by multiple timescales that are both stochastic and deterministic in nature. It is possible that the multiple timescales between amount (SD) and structure (ApEn) of force variance could be seen analogous to the two forms of current control in discrete movements proposed by Elliott (2010). More continuous control processes are made by comparing dynamic afferent information (visual intermittency) about the limb with the expected sensory feedback, while the second form of control is made by comparing limb position (spatial representation of force output) to the target location.

While mean force output, not be effected by visual intermittency, there is a trend in the right and dual handed conditions as opposed to the left improve the ability to match the force target. Task performance in these two hand conditions shows that the rate of visual feedback is relevant when considering hand dominance (Sainburg, 2010). Lack of any visible trend in the CE of the left hand is consistent with the hypothesis that the non-dominant hand is optimized for stability around a desired goal location, while reduction in CE from the right hand supports the notion that dominant limb uses predictive mechanisms based on dynamic qualities of the movement (Mutha et al., 2013).

Limitations and Future Directions

Limitations of this study are related to the duration of testing and total number of trials completed. It is likely that fatigue may have had an effect on the individual subjects however, given the randomization and counterbalancing of conditions, and similarities of the results to past work (Sosnoff et al., 2005), it is unlikely that fatigue effected the main findings of this study that there is an interaction between force and intermittency of visual information. Future studies should focus on determining the generalizability of visual control models from discrete movements to continuous isometric tracking tasks, as well as further parsing out the physiological properties from the time-dependent structure of force output. The question of hand dominance is an interesting one and should be examined further, to determine the role of hemispheric lateralization when processing intermittent visual information, and the influence on isometric force variance.

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