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Independence between the amount and structure of variability at low force levels

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Abstract

The purpose of the current experiment was to investigate the amount (standard deviation (S.D.) and coefficient of variation (CV)) and structure (approximate entropy (ApEn)) of force variability at very low force levels. Participants produced isometric force output of index finger abduction at five levels (0.4, 0.8, 1.0, 2.0, and 4.0 N) with high and low visual feedback gain. The findings showed that: subjects scaled their force output to the targets; S.D. increased non-linearly with force level and decreased with visual gain; and CV decreased with force level as well as visual gain. ApEn of the force output did not change as a function of force level, although the high gain increased ApEn in contrast to low gain. It is proposed that the recruitment of additional motor units at very low force levels does not significantly alter the structure of the force output, although it does increase the magnitude of force and its amount of variability. Overall, the findings provide evidence that the amount and structure of motor variability can be influenced by separate control processes at low force levels.

Keywords: Force variability; Motor control; Visual feedback; Irregularity

Although investigations of force production date back to the turn of the 19th century [6], they for the most part have focused on performance at moderate to high force magnitudes [8,16]. The majority of experiments have examined the amount of variability (i.e. standard deviation; coefficient of variation), even though it has been shown that time dependent and frequency measures are also needed to adequately characterize the variability of performance [13]. Traditionally, it has been maintained that there is a linear relationship between force level and variability [16,19], although under a more comprehensive examination the linear relationship is only approximated over a moderate range of force levels [3,17].

When the control of force production is examined across the operating range of the effector, a non-linear change in force variability as a function of force level is observed [3,11,17,20]. For instance, Christou et al. [3] have shown that there is a sigmoidal increase in the amount of variability (i.e. standard deviation) as a function force level ranging from 5 to 95% maximal voluntary contraction (MVC) in the quadriceps femoris. It was hypothesized that the form of the variability function is driven by the underlying neurophysiological mechanisms. Specifically, the decrease in the rate of change in the amount of variability at force levels greater than 50% MVC is the result of further increments of force resulting only from motor unit discharge rate modulation [3].

One of the few studies to examine both the magnitude and structure of force variability across the operational range of force levels found that the amount of variability has an exponential increase as a function of force level while relative variability follows a non-monotonic relation with an inflection at ∼35% MVC [17]. The time dependent structure of the force output as indexed by approximate entropy [14] also followed a non-monotonic trend as a function of force output, with the peak occurring at ∼35% of MVC. The similarity of the influence of force level on relative variability and structure of the force signal invites the conclusion that the same neurophysiological mechanisms drive the structure and magnitude of force variability. It was proposed that structure of force output and relative variability were greatest at moderate force levels (∼35% MVC) because of the availability of both motor unit recruitment and rate coding to maintain force output [17].

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Just as there are non-linearities present at the higher range of the force spectrum due to the changing contributions of neurophysiological mechanisms, it is logical for there to be non-linearities at the low end of the force production spectrum. However, the amount and structure of force variability at the low force levels (<15% MVC) have not been adequately addressed. In fact, even in studies which have examined force control over the entire operating range of the effector, this lower range is often characterized by less than two force levels (e.g. [20]). Consequently, the first goal of this investigation was to examine how the structure and amount of force variability are influenced by force levels at very low magnitudes, where increments of force are mainly due to the recruitment of additional motor units [4,10], although other mechanisms are active [11].

It is well established that visual information feedback during isometric force tasks improves performance and alters time dependent structure [18] of the force output by providing information about deviations from the target and consequently allowing for corrections. Since the amount of force variability scales to the level of force produced [17], it is possible that the increase in relative error and the increase the time and frequency structure of force output at low force levels is due to the inability to perceive and subsequently correct for the small force oscillations. According to this hypothesis there should be a greater decrease in force structure and variability at lower force levels as the gain of visual information increases. Consequently, the second purpose of this experiment is to test the proposition that there will be a decrease in the structure of force output and variability at low force levels as the gain of visual information is increased. In summary, we examine the general postulation that the amount and structure of force variability can be influenced by separate processes at low force levels.

Eleven healthy individuals, with a mean age of 22.8 years (S.D. = 3.62), from The Pennsylvania State University community voluntarily participated in the experiment. Five females and six males performed the task with the index finger of their dominant right hand. All participants provided informed consent and the procedures were approved by the local institutional review board.

Participants sat approximately 60 cm from a 17 in. computer monitor (Digiview). Their dominant hand and forearm rested on the desktop in front of them. The computer monitor had a viewing area of 800 × 600 pixels and a dot pitch width (the width of each pixel) of ∼0.07 mm. At the participants' midline, an Eltran EL-500 load cell (diameter 1.27 cm) was fixed, which measured compressive forces within an accuracy of 0.0015 N. A Coulbourn (V72-25) resistive bridge strain amplifier was used to amplify the voltage output of the load cell. The excitation voltage was set at 10 V and an amplifier gain of 100, which was sampled at 140 Hz by a 16 bit A/D board.

Participants were required to produce an isometric force with the lateral portion of the distal phalanx of their dominant index finger in an attempt to match a force target. Throughout the duration of the experiment participants were asked to restrict force production to index finger abduction. The target was displayed as a red horizontal line (1 pixel wide) spanning the entire width of the screen and was centered vertically on the monitor.

At the start of the experimental session, each participant's maximal voluntary contraction was measured. Participants were instructed to abduct their index finger against the load cell in order to generate the greatest amount of force possible. Subjects were provided continuous visual feedback. Three 6 s maximal contractions were obtained with 30 s rest between each contraction to limit the influences of fatigue. The MVC was calculated as the highest force produced over the three trials.

In the target accuracy task, participants adjusted their force output in an attempt to match a red target line displayed on the monitor screen. A series of yellow dots corresponding to the force trajectory moved from left to right across the screen over a duration of 20 s, thus providing the participant with feedback regarding force output in relation to the target level. The target line corresponded to one of five distinct force levels (0.4, 0.8, 1.0, 2.0, or 4.0 N) depending on the experimental condition.

The magnitude of visual feedback per unit force, visual gain, was experimentally manipulated by adjusting the pixel to Newton ratio. A high and low visual gain (128 and 2 pixel/N) was presented independently within each force target. For example, in the 2 pixel/N condition, a change in force output of 1 N was represented as a change of 2 pixels on the screen.

A total of 30 trials were completed by each subject. The five force conditions (0.4, 0.8, 1.0, 2.0, and 4.0 N) were randomly presented. Additionally, the order of visual gain (2 and 128 pixel/N) was balanced across each force level. Three consecutive trials were performed for each unique visual manipulation-force level condition. All participants were given 20 s rest between each trial in an attempt to minimize the effects of fatigue.

Throughout all trials participants were instructed to minimize deviations between force output trajectory and the target line. A feedback score was provided at the completion of each trial to promote performance. The score displayed was the root mean square error (RMSE) and was calculated using the equation: $(\sum (s_i - f_i)^2/n - 1)^{1/2}$, 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.

The initial 4 s and final second of force data from each trial were removed prior to analysis to avoid the initial force stabilization and/or premature cessation of force production. All data processing was performed using software written in Matlab v7 (The Mathworks, Inc.).

In order to access task performance as a function of force and visual feedback the mean, S.D. and CV of the force data were calculated. To examine how force level and gain of visual feedback influenced the structure of force output ApEn [14] was calculated. ApEn yields a single value that quantifies the time dependent structure of a time series. A highly structured signal such as an ideal sinewave would have an ApEn value approaching zero while a non-structured time series (white noise) would have a value close to 2. Thus, increases in ApEn are said to reflect an increase in the signal's time dependent structure [14].

The average of the three trials of the dependent variables discussed above were each placed independently in a two-way (5 × 2) repeated measures analysis of variance (ANOVA) with force level and visual gain as the factors. When relevant, Tukey's honestly significant difference (HSD) test was used to determine the specific effects contributing to the general ANOVA. All statistics were evaluated as significant when there was less than a 5% chance of making a Type I error ($p < .05$), and only significant effects are reported. All statistical analyses were completed using Statistica statistical package (StatSoft Inc., OK).

Maximal voluntary contraction across subjects ranged from 17.20 to 37.80 N with a mean of 25.56 N and a standard deviation of 6.32 N. As a result the five force targets on average corresponded to $1.65 \pm 0.40\%$, $3.31 \pm 0.80\%$, $4.13 \pm 1.00\%$, $8.26 \pm 2.00\%$, and $16.53 \pm 4.00\%$ MVC (mean ± S.D.). Consequently, these force magnitudes represent a portion of the force variability—magnitude relationship that to date has not been fully examined.

Statistical analyses revealed a main effect for force level [$F(4,40) = 932$; $p < .05$], gain [$F(1,10) = 15.9$; $p < .05$] and an interaction between level and gain [$F(4,40) = 3.3$; $p < .05$]. Post hoc analysis revealed that subjects were able to scale their force to the target and that they produced less force output in the low gain condition (1.42 N versus 1.60 N, respectively). The two-way interaction between force level and gain was found to be a result of the effect of gain only being significant at the 2 and 4 N force levels, with lower force output being produced in the low gain condition (1.54 N versus 1.86 N; 3.65 N versus 3.96 N, respectively).

S.D. increased as a function of force level ranging from 0.037 to 0.105 N [$F(4,40) = 28.4$; $p < .05$] (see Fig. 1A). Post hoc analysis revealed that the 4 N force level (0.105 N) had a greater S.D. than the 1 N (0.076 N) and 2 N (0.066 N) targets, which in turn were greater than the 0.4 N (0.039 N) and 0.8 N (0.037 N) force levels. Importantly, there was no significant difference in S.D. between the 0.4 and 0.8 N force levels or between the 1 and 2 N force levels (p's > .05). There was also a trend for the low gain condition (0.076 N) to have greater S.D. compared to the high gain condition (0.053 N), but traditional levels of significance were not quite reached [$F(1,10) = 4.2$; $p = .07$].

Table 1
Linear regression coefficients for the association between mean force output and S.D. of force output

Subject	Intercept	Slope	r^2
1	−4.98	0.49	0.49
2	−4.42	0.75	0.78
3	−4.49	0.17	0.12
4	−4.30	0.27	0.44
5	−4.62	0.49	0.55
6	−4.57	0.18	0.14
7	−3.71	0.34	0.28
8	−4.63	0.65	0.62
9	−4.07	0.22	0.08
10	−3.71	0.34	0.28
11	−3.72	0.39	0.20

$^{*}p < .05$.

Fig. 1B shows that the CV decreased as a function of force level and visual gain. Statistical analysis revealed a main effect for force level [$F(4,40) = 14.3$; $p < .05$] and gain [$F(1,10) = 5.7$; $p < .05$] and a two-way interaction between force level and gain [$F(4,40) = 5.2$; $p < .05$]. Post hoc analysis found that CV significantly decreased from 0.12 in the 0.4 N force level to .04 in the 4 N force level. The higher gain (0.06) had a lower CV compared to the low gain condition (.10). The two-way interaction was found to be a result of the lack of effect of gain at the highest force level.

Although it was found that there was an increase in absolute force variability (S.D.) with increases in mean force output, the ANOVA conducted was unable to describe the relationship between force variability and magnitude of force output. To test if there is a linear relationship between force variability and force magnitude linear regression was performed on the logarithm of the data. Table 1 lists the intercept, slope and amount of variance accounted for by the regression functions for each subject. Sta-

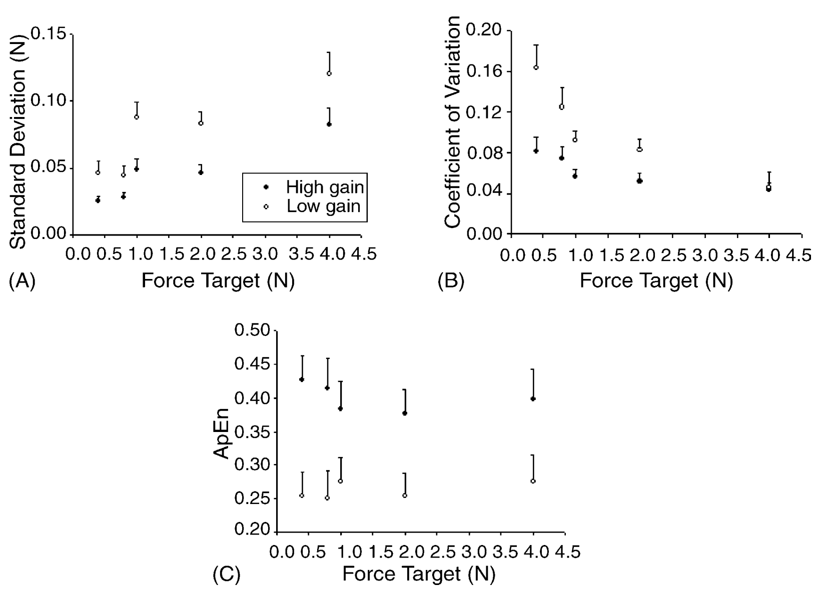

Fig. 1. (A) Standard deviation, (B) coefficient of variation, and (C) approximate entropy of force output as a function of force level and visual gain. Values reported are means plus standard errors.

tistical analysis found that the slopes of the regression functions were significantly different than 1 ($t = -10.6$; $p < .05$). These findings confirm that there is not a linear relationship between force variability and force magnitude at low force levels.

Fig. 1C shows that there is greater irregularity in the higher visual gain condition and no effect of force magnitude on the irregularity of force output. Statistical analysis confirmed these observations with no main effect for force level [$F(4,40) = .35$; $p > .05$] and a main effect for gain [$F(1,10) = 13.1$; $p < .05$]. The high gain condition (0.41) was found to have greater force irregularity than the low gain condition versus (0.27).

The purpose of this experiment was to investigate at very low levels of isometric force output: (1) the amount and structure of force variability; and (2) the influence of visual feedback on these properties of force variability. The majority of studies that have examined the influence of force level on force variability have focused on moderate to high force levels. For instance, Schmidt et al. [16] examined discrete force production over a moderate range of force levels and proposed that the amount of variability (S.D.) of force production linearly scales with magnitude. Although the hypothesis of linear force-to-force variability function has served as a founding principle in several formulations of motor control [7,9], there is a large amount of research, which has shown that this relation does not hold at the high levels of force output [3,17,20].

Congruent with both of these investigations, the current study reveals that force variability does not increase linearly with force magnitude at the low end of the force production spectrum. Indeed, there was no change in S.D. at the two lowest force levels in this investigation. This floor effect is in line with Christou et al. [3] suggestion that the logistic trend with its multiple scaling regions is the most feasible function to describe the relation between force variability and force magnitude. Additionally, the lack of linearity between the magnitude of force output and force variability at low force levels is in contrast to extant theories of motor control [7,9]. It is proposed that these theories of motor control are only able to account for behavior within a limited range and need to be reconceptualized in order to adequately account for the entire spectrum of human behavior.

Fluctuations in force output have been hypothesized to be due to the unfused firing of motor units [5] and the variability of the discharge rate [11]. Jones et al. [8] have provided evidence that there is no contribution of mechanical components of force generation to force variability. However, since this study only examined force output from 20 to 80% MVC, it is possible that at low levels of force production there is an influence of the mechanics of muscular contraction. Moreover, Jones et al. [8] proposed that the scaling of variability to force magnitude is due to three properties of the motor unit pool: (1) large range of twitch forces; (2) distribution of recruitment thresholds; and (3) orderly recruitment of motor units. The lack of scaling of variability observed in the lowest force levels in the current study is most likely due to lack of a large range of motor unit twitch forces and a distribution of recruitment thresholds.

In contrast to Slifkin and Newell's findings [17] there was no influence of force magnitude on the structure of force output. Unlike the magnitude of force variability there have been very few experiments examining the underlying neuromuscular properties which contribute to the structure of force magnitude. ApEn of force output has previously been reported to increase with force magnitude to about 35% MVC then decrease incrementally. The inflection of this relationship was proposed to be due to the use of both motor unit recruitment and firing rate modulation to maintain force at this moderate level [17]. To date this proposition remains untested. Unlike distributional measures of performance (i.e. mean, S.D., etc.), ApEn is not influenced by the magnitude of the signal, but rather indexes the signal's time dependent structure. Lower values of ApEn corresponding to a more structured output are theorized to be due to a decreased number of control processes [14]. As such the observation that ApEn is not influenced by the 10 fold increase in force magnitude at the lower end of the force spectrum is congruent with the utilization of the same relative influence of control processes. As motor unit recruitment is the main process to increase force level at this low range of force output [4,10], it is postulated that this mechanism does not influence the structure of the force output at low force levels.

The findings were clear in showing that the amount of force variability decreased and force irregularity increased with more precise levels of visual information. This observation is in line with the well-documented contributions of visual feedback to motor performance [22]. However, there are some reports that have shown that the availability of visual feedback has no influence on force variability [3,20]. The majority of these investigations that have demonstrated a null effect of visual feedback examined force variability over short timescales (<1 s) and/or examined the aggregate of force output over short timescales. Sosnoff and Newell [18] have shown that in the control of isometric force production there are multiple visuomotor control processes operating at rates up to 12 Hz. Consequently, the use of either of the above methodologies will minimize the influence of these visual control processes.

The increase in force irregularity with increased visual information feedback (high gain condition) is consistent with previous reports [18]. Increased visual feedback information allows for the updating of the multiple feedforward and feedback processes that compose the visual control loop of isometric force output [18]. It is this updating over an increasing range of shorter time scales that drives the decrease in force signal time dependent structure. The strong effect shown here of visual information on the structure of force output suggests that the neuromuscular processes influenced by visual feedback are distinct from those organizing increments of force at low levels.

It is relevant that Schmeid et al. [15] have reported an increase in motor unit synchronization and changes in motor unit inhibition [12] with increases in visual information during a tracking task. It has also been demonstrated that difficult bimanual limb rhythmic movements are facilitated with visual feedback that is associated with increased excitability of the descending motor pathway [2]. Vaillancourt et al. [21] report that changes in visual scale do not alter motor unit firing rate variability. Consequently, it is possible that either motor unit synchronization and/or motor unit pool excitation is the mechanism via which visual information contributes to force control.

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