

# Visual information gain and the regulation of constant force levels

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**Abstract** Visual information is essential in human motor control, and especially in the continuous modulation of isometric force. The gain of visual feedback, that is, the amount of space used to represent change in force, has been shown to affect both the magnitude and time-dependent properties of variability in the force output. However, little is known regarding the interacting effects of visual gain and target force level on force variability and whether the effects of force level can be mediated by a gain that is adjusted to force level. We examined the effect of different types and levels of visual feedback gain and target force level (1, 2, 4, 8, and 12 N) on the magnitude (standard deviation, SD) and regularity (approximate entropy, ApEn) of isometric force variability. Young adults performed an isometric force task with high and low levels of constant (same gain level for all forces) and scaled (proportional to force level) gain. The magnitude of force variability increased exponentially as a function of force level once the SD was corrected for the limits of the display area. The time-dependent properties of force variability remained constant across force levels when gain was adjusted to force level. These findings suggest that the time-dependent properties of force variability are the result an interaction between visual feedback and task force level demands, while the increases in SD over force levels are primarily due to the invariant properties of human muscle and the motor system.

**Keywords** Isometric force · Visuomotor control · Entropy · Gain · Visual feedback · Equilibrium-point hypothesis

## Visual information gain and the regulation of force variability

Human motor behavior involves the use of visual information as a mechanism for the guidance of action (e.g., Milner and Goodale 1993; Ellermann et al. 1998). One widely used paradigm in the study of manual control is that where a subject adjusts their motor response on the basis of visual feedback from a computer screen. This paradigm provides an environment that allows for a range of sensorimotor processes to be investigated (see Sheridan and Ferrell 1974; Miall 1996). In this research protocol, a well established finding is that the *gain* of the visual feedback, that is, the ratio of the space on a display (e.g., number of screen pixels) used to represent change in motor output (e.g., force) has a strong influence on motor performance (Wickens 1984; Jagacinski and Flach 2003). Generally, it has been shown that there is an inverted U-shaped relation between gain and motor performance, whereby increasing gain up to a certain level enhances performance but continued increments in gain can also lead to performance deficits (Newell and McDonald 1994; Beuter et al. 1995; Rougier et al. 2004; Sosnoff and Newell 2006). Furthermore, higher levels of visual gain have been shown to delay the onset of fatigue when maximal contractions are sustained for as long as possible (Mottram et al. 2006). However, there are a variety of ways in which visual gain can be manipulated, and this experiment focuses on contrasting the effects of gain that is constant across force levels against gain that is set relative to the task demands.

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Visual information is especially important in the continuous manual control of isometric force. This is because haptic information from cutaneous and proprioceptive receptors alone is insufficient to sustain the target force for even the briefest of periods in the absence of visual information. The necessity of visual feedback to maintain a constant isometric force level is evident in that isometric force output degrades as quickly as 0.5 s after the withdrawal of vision (Vaillancourt and Russell 2002; Davis 2007). Naturally, the properties of visual feedback, more specifically, visual gain has been shown to have a significant effect on force variability (Sosnoff et al. 2006; Hong et al. 2008). Higher levels of visual gain were found to reduce the magnitude of variability, as indexed by the SD of the force output. The force output was more irregular (as indexed by approximate entropy) at moderate levels of visual gain, but decreased at the extremes, resembling an inverted-U.

Visual information, however, is not the only factor that has a significant effect on force variability. In isometric force production tasks, the magnitude and time-dependent properties of force variability have been shown to change as a function of the target force level in both discrete and continuous force tasks. In discrete isometric force tasks where the subject is required to generate a force pulse of a given magnitude through isometric contractions, the variability of force output increases as a negatively accelerating exponential growth to an asymptote with increments of peak force level or impulse size (Newell et al. 1984; Carlton and Newell 1993). Thus, as the target force of the pulse increases, the rate at which variability increases as a function of force level decreases as force variability nears the asymptote. When the task demands are continuous production of force, i.e., a sustained isometric force level of a set duration, the magnitude of force variability have been shown to generally increase exponentially with increments in force level (e.g., Slifkin and Newell 1999, 2000; Moritz et al. 2005; Hong et al. 2007). However, it should be noted that isometric force variability has also been found to change as S-shaped function of force level that can be modeled by a logistic equation (Christou et al. 2002).

A candidate explanation of exponential growth in magnitude of force variability as a function of force level is the equilibrium point ( $\lambda$ ) hypothesis (Feldman 1966). In the  $\lambda$  hypothesis, muscle forces are generated when the muscle is shifted away from its rest length or equilibrium point. However, in isometric tasks that require the continuous force generation over a period of time, the muscle cannot achieve its new rest length and has to oscillate between equilibrium points. Assuming a constant (over- or under-shoot) error whenever the equilibrium point is shifted to

meet the target force level, the  $\lambda$ -model would predict an exponential increase in standard deviation (SD) of the force output as a function of force level (see Hong et al. 2007). One hypothesis is that the changes in magnitude of isometric force variability as a function of force level are primarily a reflection of the invariant characteristics of human muscle.

In addition to changes in the magnitude of variability (SD), the time- and frequency-dependent properties of the force output has also been found to change as a function of force level. For example, Slifkin and Newell (1999, 2000) observed an inverted-U pattern of change in the irregularity of the force output (as indexed by approximate entropy, ApEn) with increasing force level. The highest level of irregularity in the force output was observed at moderate force demands, which was approximately 35% of the subjects' maximal force output. It has been proposed that this function is a reflection of the presence of a larger pool of motor unit recruitment strategies that can be used to regulate the force output (Slifkin and Newell 1999).

Although the effects of force level and visual gain on both the magnitude and time-dependent properties of force variability are well understood in isolation, less is known regarding their interaction. In situations where a constant gain is employed irrespective of force level, the effective visual gain is reduced as force level is increased. This is because force variability grows as a function of force level, and will encompass a greater portion of the display. For example, a screen resolution of 600 p on the vertical axis, a gain of 128 p/N (pixels-per-Newton) results in 2.34 N ( $1/128 \times 300$ ) above the target force line (assuming the target is placed in the center of the display), and 2.34 N below it. For a 12 N target force, the vertical axis of the screen is able to represent 39% of the target force. A target force of 16 N at 128 p/N gain allows the screen to only display up to 29% of the target force. Thus, effective visual gain is reduced at higher force levels, as the number of Newtons that can be presented on-screen remains the same even though the variability of the force output is increasing as a function of force level.

The loss of effective visual gain at high force levels makes detection of errors in the force output more difficult, and it also increases the possibility that the limits of the screen resolution will be exceeded. Although the limits of the visual display are specific to the manual control paradigm, it serves in a general sense as a reflection of the limits to the human field of vision. When these limits are exceeded, gaps in visual information result, creating *intermittency* in the feedback. Intermittency in visual feedback has been shown to affect motor performance (Elliott 1990; Miall et al. 1993; Robertson et al. 1994), and more specifically, increase the amount of force variability

and reduce the irregularity of the force output (Slifkin et al. 2000). It has also been shown that visual gain and intermittency of visual feedback have compounding and compensatory effects on the time-dependent properties of force variability (Hong et al. 2008). Low levels of visual gain were found to reduce the irregularity of the force output, an effect compounded when low gain is paired with a high level of intermittency in the visual feedback. However, the irregular pattern of the force output can be maintained when the feedback is highly intermittent feedback if paired with a high visual gain. A similar result can be obtained if feedback with low visual gain is paired with minimal intermittency. Thus, the gaps in visual information due to the visual feedback exiting the limits of the display may play a role in the interactive effects of visual gain and force level.

The goal of this experiment was to examine the interaction between force level and visual gain on the magnitude and time-dependent properties of force variability in a continuous isometric force task. This interaction was examined using *constant* and *scaled* types of visual gain that were contrasted over a range of force levels. The constant gain remained constant across all force levels, while the scaled gain was set as a quotient of the force level. Special attention was placed on the limits of the visual display, where the amount of time for which the visual feedback was not available to the subject was measured and included in the data analysis. The manipulations of force level and visual gain were implemented in order to delineate the effects of gain and force level on force variability and yield further insight into the sensorimotor processes of manual control.

## Methods

### Subjects

Twelve college-aged individuals (6 male, 6 female, mean age = 22 years) volunteered as subjects in this study. All subjects were right-hand dominant (as determined by the preferred writing hand) and were free of any neuromuscular disorders or injuries to the limbs. Informed consent was provided prior to participation, with approval for the experimental protocol from the Pennsylvania State University Institutional Review Board.

### Apparatus

A 3-dimensional load cell (ATI Industrial Automation, Garner, NC) was used to measure the isometric force output produced by the subjects. Force data were collected at a sample rate of 100 Hz. The subjects' palms were

placed in a prone position, and were required to maintain both the surface of their palm, fingers, and forearm against the table. Motion at the elbow was constrained by two cloth-covered wooden blocks that were adjusted to the size of the individual participant's forearm. The subjects' middle fingers were placed within a semi-circular constraint that isolated the force production primarily to the first dorsal interosseus. The experimental setup was similar to Hong et al. (2007, 2008).

### Task and procedures

Maximal voluntary contraction for each subject was determined at the beginning of the experimental session. Subjects were instructed to exert maximal isometric force by pushing their index finger against the surface of the load cell as hard as possible. Force was generated by pushing against the load cell toward the midline of the body. Each subject completed two MVC trials of 10 s with 20 s rest between each trial. The average of the highest force value produced in each trial determined the respective MVC for each individual.

Following a rest period, the experimental trials commenced. The subjects were required to maintain a sustained isometric contraction for a period of 15 s. The target force level was represented as a red line against a black background on a computer screen. The computer monitor on which the visual feedback was provided possessed a screen resolution of 800 (width) × 600 (height) pixels. Online feedback of the force output was provided via a force trajectory (plotted with white pixels presented at a rate of 56 Hz) that passed from the left to right of the screen as the trial progressed. Upon completion of each trial, the subject was provided with the RMSE (root mean square error) as post-trial feedback. Subjects were informed that their performance in the first 4 s and last 1 s of the trial would not be factored into their RMSE scores. This was to allow the subjects the first 4 s to achieve the target force and the last 1 s was removed in order to minimize the role of fatigue and other preservative effects at the end of the trial. RMSE was calculated as:

$$\text{RMSE} = \sqrt{\frac{\sum (F - f_i)^2}{(n - 1)}} \quad (1)$$

where  $F$  is the target force value and  $f_i$  is the  $i$ th force sample in the time series.

Subjects were required to perform the task at five target force levels, namely, 1, 2, 4, 8 and 12 N. The gain of the visual feedback was manipulated as the number of pixels that would reflect 1 N of change on the computer monitor. Subjects completed three trials at all of the aforementioned force levels under four different gain conditions: (1)

Constant Low Gain (CLG, 2 p/N); (2) Constant High Gain (CHG, 128 p/N); (3) Scaled Low Gain (SLG, 1:1 Target Force to Screen Size Ratio); and (4) Scaled High Gain (SHG, 8:1 Target Force to Screen Size Ratio). For the scaled gain conditions, the target force to screen size ratio is calculated as the gain divided by the screen size (always 600 pixels), multiplied by the target force. Thus, performing a 1 N force task with a gain of 600 p/N yields a 1:1 ratio. The p/N values for the various gain conditions and force levels are presented in Table 1.

#### Dependent variables

Similar to the RMSE scores presented following each trial the first 4 s and last 1 s were removed from all of the analyses of all trials. This reduced the amount of data analyzed to the middle 10 s of each trial.

The magnitude of force variability was assessed with the standard deviation (SD) of the force output. The time-dependent properties contained within the isometric force fluctuations were examined through the irregularity measure of approximate entropy (ApEn—Pincus 1991). ApEn is obtained from the logarithm of the average recurrence of sequences (within a tolerance of  $r$ ) of length  $m$  with respect to sequences of length  $m + 1$  for a unit variance normalized time-series. Parameters  $m$  and  $r$  were set at 2 and 0.2, respectively. Essentially similar to information entropy (Shannon 1948), ApEn is calculated as  $\log(1/p)$ , where  $p$  is the probability of occurrence of a given event in the case where all events are equally probable. Written as an equation, the ApEn algorithm is:

$$\text{ApEn}(\vec{X}, m, r) = \log \left[ \frac{C_m(r)}{C_{m+1}(r)} \right] \quad (2)$$

In order to correct for the percent of time, the dependent variables would have to be adjusted according to the probability of the force feedback remaining within the dimensions of the screen. The SD adjustment was achieved by multiplying the SD by the percentage of time the feedback was on-screen. With ApEn, however, eliminating

data from the time-series would alter the dynamic pattern of the force output in a way that could lead to spurious conclusions. The rationale for performing this adjustment is that ApEn (Eq. 2) accounts for time points for which the feedback was both on- and off-screen. Understanding that the percent of time on-screen is essentially a probability, ApEn can be converted into conditional entropy (see Ash 1965) by multiplying the probability ratio of  $[C_m/C_{m+1}]$  by the probability of the feedback remaining on-screen,  $P_s$ , yielding the equation:

$$\text{ApEn}(\vec{X}, m, r) = \log \left[ \frac{C_m(r)}{C_{m+1}(r)} \times P_s \right] \quad (3)$$

The ApEn measure here thus provides an index of the irregularity of the force output conditional upon the force value remaining within the limits of the screen resolution.

The dependent variables were examined with a 4 (Gain)  $\times$  5 (Force) repeated measures ANOVA using SPSS. Violations of the sphericity assumption were corrected with a Huynh–Feldt adjustment to the statistical degrees of freedom.

## Results

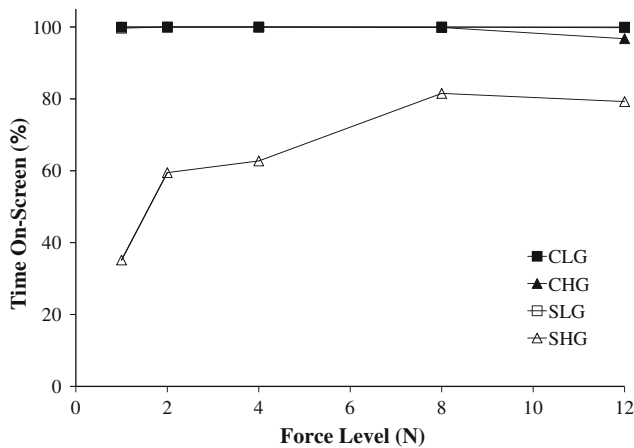
The maximal force generated by the subjects was  $M = 25.2$  N,  $SD = 5.7$  N, falling within a range of 16.3–34.9 N.

#### Percent of trial on-screen

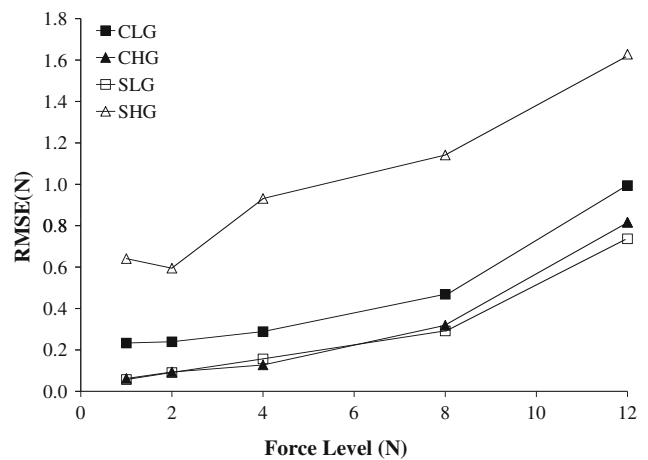
Figure 1 shows the mean time on screen as a function of force level and gain conditions. There was a significant gain  $\times$  force level interaction [ $F(3.4, 37.1) = 5.89$ ;  $p = 0.002$ ] as well as gain [ $F(1.0, 11.1) = 24.98$ ;  $p < 0.001$ ] and force [ $F(2.9, 31.9) = 5.31$ ,  $p = 0.005$ ] main effects on the percent of trial time spent on-screen. The interaction occurred because force level influenced time on-screen for the SHG condition but not the other visual gain conditions. Post-hoc analysis found no significant ( $p > 0.05$ ) differences across force levels for the CLG, CHG, and SLG conditions. All the pairwise comparisons for the different force levels in the SHG condition were significant ( $p < 0.05$ ) except for force levels of 8 and 12 N. Due to the relatively high heterogeneity of variance, pairwise comparisons were also conducted using non-parametric, Wilcoxon Signed Ranks Tests. Similar to the parametric analyses, we found no significant ( $p > 0.05$ ) differences across force levels for the CLG, CHG, and SLG conditions. All of the Wilcoxon comparisons for the different force levels in the SHG condition were significant ( $p < 0.05$ ) except for the following: (1) 2 vs. 4 N; (2) 4 vs. 8 N; (3) 4 vs. 12 N; (4) 8 vs. 12 N.

**Table 1** Summary of the p/N ratios for different gain conditions and force levels.

Gain condition	Target force				
	1 N	2 N	4 N	8 N	12 N
Constant low gain	2	2	2	2	2
Constant high gain	128	128	128	128	128
Scaled low gain	600	300	150	75	50
Scaled high gain	4,800	2,400	1,200	600	400



**Fig. 1** Percent of time on-screen for the visual feedback under the different gain and force levels. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)



**Fig. 2** RMSE as a function of force level under the various gain conditions. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)

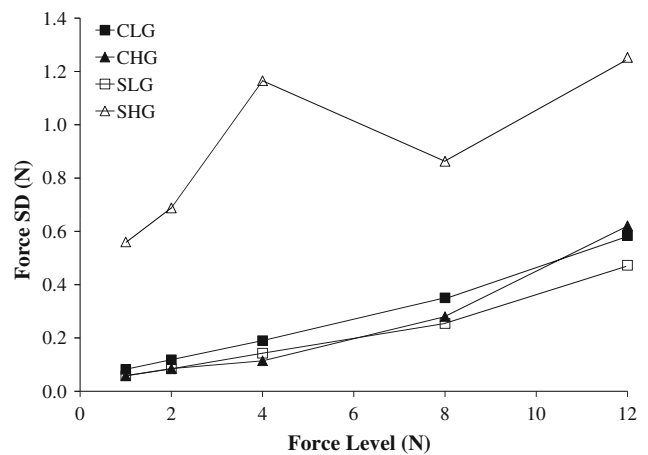
RMSE

Figure 2 presents the average RMSE for the four different gain conditions across the various force levels. Significant gain [ $F(1.0, 10.5) = 6.38; p = 0.024$ ] and force [ $F(1.9, 19.4) = 8.3; p < 0.01$ ] effects were observed. The gain  $\times$  force level interaction [ $F(3.5, 37.9) = 0.2; p = 0.91$ ] was not significant. Post-hoc analysis of the gain effect found that the pairwise comparisons of SLG versus CHG and SHG versus CLG were not significantly different ( $p > 0.05$ ). The post-hoc analysis of the remaining pairwise comparisons (i.e., SLG vs. SHG; SLG vs. CLG; CHG vs. SLG; CHG vs. SHG) yielded significant differences ( $p < 0.05$ ).

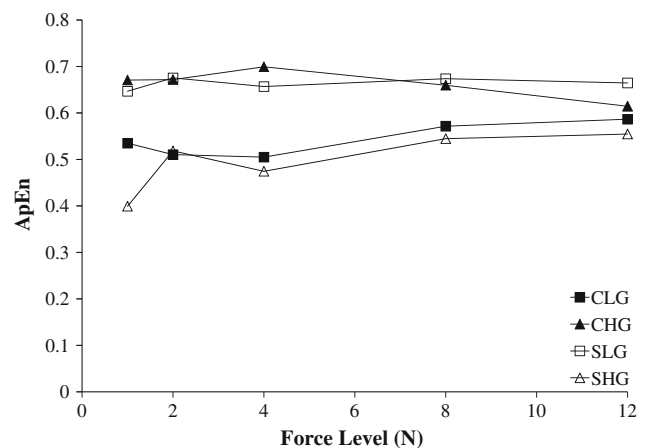
Unadjusted data

Figure 3 displays the variability of force (SD) for the unadjusted data. There were significant effects of gain [ $F(1.0, 11.2) = 9.4; p = 0.01$ ] and force [ $F(2.1, 28.9) = 5.8; p = 0.008$ ] on the SD of the force output. The gain  $\times$  force interaction was not significant [ $F(3.1, 33.9) = 0.55; p = 0.657$ ]. The scaled high gain condition (SHG) had significantly greater variability than the other gain conditions. Increments of force level led to successively higher levels of force variability.

The ApEn data as a function of gain condition and force level are shown in Fig. 4. A significant gain  $\times$  force interaction [ $F(8.5, 94.0) = 2.02; p = 0.049$ ] and gain [ $F(1.8, 20.2) = 10.26; p = 0.001$ ] effect were found for the ApEn data. The effect of force level [ $F(1.8, 19.4) = 0.91; p = 0.406$ ] on ApEn was not significant. The constant high gain and the scaled low gain had greater irregularity than the other two conditions. The interaction was due to the lower ApEn score of the scaled high gain



**Fig. 3** SD as a function of force level under the various gain conditions. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)



**Fig. 4** ApEn as a function of force level under the various gain conditions. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)

condition at the low force level that was not present at other force levels.

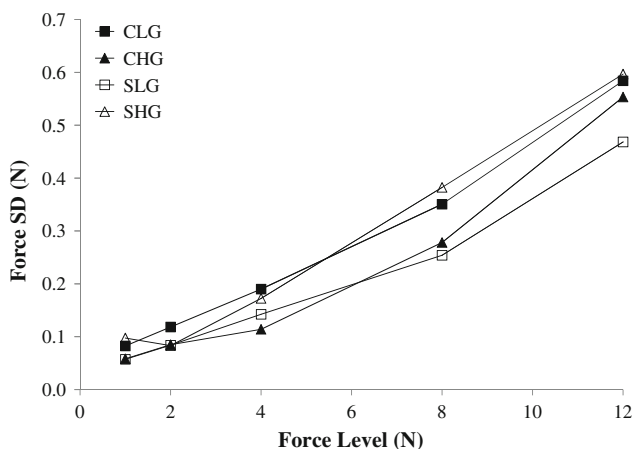
### Adjusted data

Figure 5 shows the force SD as a function of force level and gain condition for the adjusted data. Once the SD values are adjusted for the percentage of trial for which the visual feedback remained on-screen, only the main effect of force level [ $F(1.2, 13.0) = 25.8$ ;  $p < 0.001$ ] was significant. The effect of gain [ $F(1.7, 18.5) = 2.2$ ;  $p = 0.141$ ] and the gain  $\times$  force interaction [ $F(3.1, 54.1) = 0.59$ ;  $p = 0.704$ ] were not significant. As with the uncorrected data the force variability increased at an increasing rate with increments of force level.

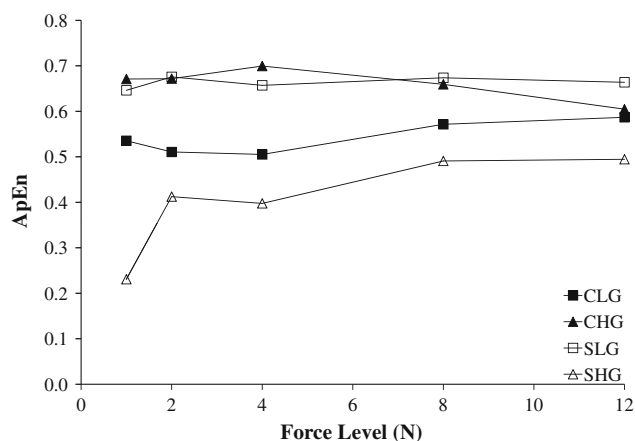
With the ApEn calculations made conditional upon the visual feedback remaining on-screen, a significant gain  $\times$  force interaction [ $F(6.5, 71.6) = 3.02$ ;  $p = 0.009$ ] and gain effect [ $F(1.7, 18.5) = 19.13$ ;  $p < 0.001$ ] were observed (Fig. 6). The effect of force level [ $F(1.9, 20.6) = 1.92$ ;  $p = 0.173$ ] on ApEn was not significant. The interaction was due to the lower ApEn value at the 1 N force level for the scaled high gain condition.

### Discussion

The results of this experiment demonstrate the independence of the magnitude and time-dependent properties of force variability as a function of visual gain and force level. Magnitude of force variability increased as an exponential function of force level, a result that was consistent across all visual gain conditions once the percentage of the trial where the feedback exited the screen was accounted for.



**Fig. 5** SD corrected for the visual feedback percent of time on-screen as a function of force level under different gain conditions. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)



**Fig. 6** ApEn corrected for the visual feedback percent of time on-screen as a function of force level under different gain conditions. (note: *CLG* constant low gain, *CHG* constant high gain, *SLG* scaled low gain, *SHG* scaled high gain)

We found that the change in the time-dependent properties of force variability as a function of force level could be negated when visual gain was adjusted to be proportional to force level.

### Task performance—RMSE

The results showed that the best performance on the task, i.e., the lowest error was obtained when: (1) a constant high gain was employed; and/or (2) the amount of force that could be represented over the entire screen height was set to be equal to the target force level. The extreme gain conditions (most and least sensitive) resulted in the poorest performance on the task. Error was highest in the SHG condition where the screen size was set at eight times the target force. It is important to note, however, that the error in the SHG condition was not significantly different from the CLG condition. These findings support the hypothesis that an optimal level of visual gain exists. Once this optimum is exceeded, the increased precision of the visual information cannot be exploited resulting in a ceiling effect that can also lead to decrements in motor performance (Newell and McDonald 1994).

### Magnitude of force variability

The effect of force level on the uncorrected SD data was consistent with previous findings that have shown the magnitude of force variability to increase exponentially with force level (Slifkin and Newell 1999, 2000; Hong et al. 2007). In this current study, the range of force levels from 1 to 12 N was approximately 4–50% of the subjects' average MVC. It is interesting to note that even though the range of forces employed in the aforementioned studies (Slifkin and Newell 1999, 2000; Hong et al. 2007) fell

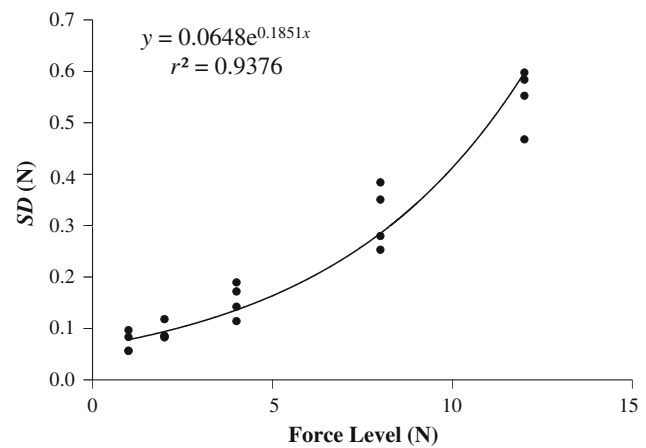
between 5 and 95% of MVC, the exponential growth in SD as a function of force level was still observed.

We did not, however, observe the S-shaped change in force variability as a function of force level presented in Christou et al. (2002). The most likely explanation is that the task employed by Christou et al. (2002) involved the much larger quadriceps muscle, while the current and prior studies (Slifkin and Newell 1999, 2000; Hong et al. 2007) that have found exponential change involved muscles in the fingers and hand. However, the fact that Christou et al. (2002) employed a range of force levels between 2 and 95% of MVC suggests that the different patterns of change in force variability are not likely the result of the range of force levels employed, but rather, related to the size of the joints and muscles involved in the task.

Gain significantly affected the SD, but this difference was restricted to the scaled high gain condition (SHG), as the SD values were similar across the remaining gain conditions. In the SHG condition, the subjects actually spent a significant portion of the trial duration without any visual feedback whatsoever (Fig. 1), especially at the lowest force level. This creates an inadvertent increase in the intermittency of the visual feedback that resulted in greater motor variability, a finding that is consistent with previous studies (Elliott 1990; Robertson et al. 1994; Slifkin et al. 2000). This finding provides a different perspective on the decline in motor performance beyond the optimal gain level. Rather than a limitation on neural/cognitive information processing capacity (Newell and McDonald 1994), our current findings suggest that the decrement in performance may be at least in part the result of the limits of display size and visual field.

It is interesting to note that the gain effect on force SD could be negated by correcting the data for the intermittency generated by the overly sensitive visual display. By simply multiplying the SD values by the percentage of time the visual feedback remained on-screen, we were able to mediate the negative effects of the extremely high levels of visual gain. Once this adjustment was performed, the increases in the magnitude of force variability as a function of force level became uniform across all the visual gain conditions (Fig. 7). These findings provide further support for: (1) the idea that the change in magnitude of isometric force variability as a function of force level is related to the inherent properties of the human musculature (Hong et al. 2007); and (2) the compensatory nature of the spatial (gain) and temporal (intermittency) properties of visual feedback (Hong et al. 2008).

At the neural level, our findings are in-line with previous observations that the spatial and temporal properties of visual information are encoded similarly in the visual neurons through a compensatory mechanism (de Ruyter van Steveninck et al. 1996). At the muscular level, these



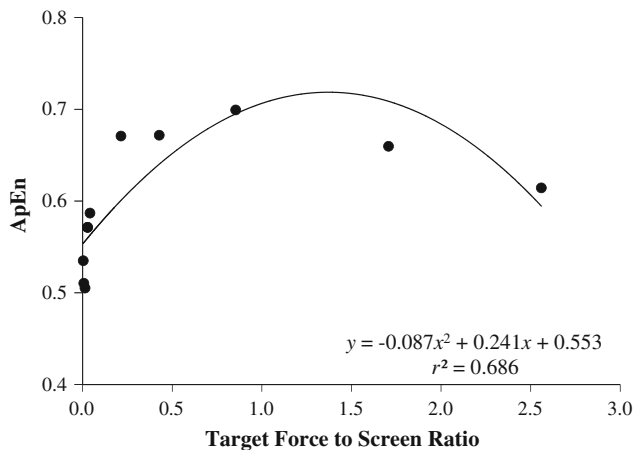
**Fig. 7** SD of the force output averaged across subjects as a function of force level for all visual gain conditions. The data are fitted to a 2-parameter exponential function

findings on force variability can be linked to the seminal work by Feldman (1966), and suggest that the changes in force variability as a function of force level reflect the invariant properties of human muscle and, potentially, some form of neural or motor noise (Faisal et al. 2008). The substantiation of the exponential increase in magnitude of variability as a function of both absolute and relative force levels provides further evidence of the potential for equilibrium-point control of isometric force with a constant error.

#### Time-dependent properties of force variability

The ApEn results show a significant interaction between visual gain and force level. An interesting aspect to this finding is that both the corrected and uncorrected ApEn data remained constant with increasing force levels when gain was set to maintain a 1:1 ratio between force level and screen height. In the scaled high gain condition, when gain was set by maintaining an 8:1 target force to screen size height, an increase in ApEn was observed as force level was increased. At the lower force levels, this level of gain would have been overly sensitive, but, as force level is increased, the likelihood of the visual feedback exceeding the limits of the visual display decreases. This finding is similar to previous studies that have shown that the availability of visual feedback results in more irregular patterns of motor performance (Beuter et al. 1989; Slifkin et al. 2000; Hong et al. 2008; Hong and Newell 2008a, b).

In order to further illustrate this gain-force level interaction, we generated a dimensionless index of visual feedback that encompasses both gain and force simultaneously, namely the target force-to-screen ratio that was used to set the pixel-to-Newton values for the scaled gain conditions. This ratio was obtained by dividing the gain by



**Fig. 8** ApEn as a function of the target force-to-screen height ratio. A line of best fit obtained from a second order polynomial regression is presented

screen height and multiplying the result by the target force, resulting in a dimensionless variable that represents the visual gain relative to the task demands. When the uncorrected ApEn data for the constant gain conditions are plotted against the target force-to-screen ratio, an inverted-U pattern of change that can be captured by a quadratic function emerges (Fig. 8). This is similar to the quadratic change in ApEn as a function of force level found by Slifkin and Newell (1999, 2000).

This new analysis of visual gain reveals that the time-dependent properties of force variability are driven primarily by visual feedback, as the effect of force level on irregularity can be negated as long as the spatial sensitivity of the feedback is maintained. Although the  $r^2$  value of the quadratic function is fairly high, there is observable asymmetry in the data, suggesting that the scale on the abscissa may be nonlinear, an issue that should be explored in future research projects. It remains possible that the dimensionless variable is reflective of an underlying process that captures the interaction between task demands and visual gain that can be revealed through further empirical studies.

Our current findings also support the hypothesis that the changes in the irregularity of force output reflect the interaction between the availability of potential motor unit combinations that can be recruited for the task and the information available in the environment. One would posit that the greater amounts of visual information available at higher levels of visual gain resulted in the recruitment of the lateral cerebellum in the processing of visuomotor signals, which has been shown to reduce motor variability in a related experimental paradigm (Vaillancourt et al. 2006). The gain  $\times$  force level interaction found in this study extends the work of Slifkin and Newell (1999, 2000), and provides further evidence that the variation in the

employment of these available configurations is dependent on the availability of information from the environment (Hong and Newell 2008a). Our findings provide further evidence for the independence of magnitude and time-dependent properties of force variability and the interaction between the properties of visual information and task demands.

It appears that the statistical properties of motor variability (rather than its magnitude alone) change systematically with the demands of the task and the information available in the environment (Hong and Newell 2008a, b). From the perspective of the conceptual framework of Faisal et al. (2008), the additional information from the environment could be averaged in order to reduce the presence of sensory noise. This reduction in noise would have allowed for an increase in the number of small amplitude corrections to the force output that would be reflected in an increase in ApEn of the force trace. However, parsing the deterministic (force corrections) from the stochastic (neural, sensory, and motor noise) influences on isometric force control remains an issue for future studies.

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