Visual Feedback Attenuates Force Fluctuations Induced by a Stressor

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ABSTRACT

CHRISTOU, E. A. Visual Feedback Attenuates Force Fluctuations Induced by a Stressor. Med. Sci. Sports Exerc., Vol. 37, No., 12, 2126–2133, 2005. Purpose: The fluctuations in force during a steady contraction can be influenced by age, vision, and level of physiological arousal. The aim of this study was to determine the effects of a stressor on the force fluctuations and information transmission exhibited by young, middle-aged, and older adults when a pinch-grip task was performed with and without visual feedback. Methods: Thirty-six men and women (19–86 yr) participated in a protocol that comprised anticipatory (30 min), stressor (15 min), and recovery periods (25 min). The stressor was a series of noxious electrical stimuli applied to the dorsal surface of the left hand. Subjects sustained a pinch-grip force with the right hand at 2% of the maximal voluntary contraction force. The normalized fluctuations in pinch-grip force (coefficient of variation), information transmission (log2 signal:noise), and the spectra for the force were quantified across the 70-min protocol. Results: Removal of visual feedback exacerbated the force fluctuations (3.83 ± 3.15 vs 2.82 ± 1.64%) and reduced the information transmission (5.01 ± 0.86 vs 5.34 ± 0.71 bits) only during the stressor period. The effect was similar for all age groups. Older adults exhibited greater force fluctuations and lower information transmission compared with young and middle-aged adults, especially during the stressor period. The impairments in fine motor performance during the stressor were associated with an enhancement of the power at 1–2 Hz in the force spectrum ($R^2 = 0.41–0.52$). Conclusion: Removal of visual feedback increased the force fluctuations and decreased information transmission during a stressor period, which suggests that integration of visual feedback can attenuate the stressor-induced enhancement of synaptic input received by the motor neuron pool. Key Words: FORCE VARIABILITY, INFORMATION TRANSMISSION, AGING, AROUSAL, 1- TO 2-HZ FORCE OSCILLATIONS

Older adults experience greater variability in motor output compared with young adults during numerous motor tasks. This age-associated increase in motor output variability appears to be exacerbated during contractions with low levels of force (8), greater task demands (3,28), and removal of visual information about the task (19). These age-associated differences in the control of motor output are related to task variations. Recently we used an alternative strategy to determine the influence of age on motor output. Specifically, we altered the levels of physiological arousal (stress) in young, middle-aged, and older adults by applying noxious electrical stimulation on the noncontracting hand to determine its effects on the variability of force during a low-force pinch-grip task (4,15,16). This stressor increased the amplitude of the force fluctuations in young and old adults.

At least two physiological mechanisms can alter the synaptic input received by the motor neuron pool during exposure to a stressor and thereby influence the force fluctuations. First, an increase in the monoaminergic drive to the motor neuron pool (12) causes the release of neuromodulators from the brainstem neurons to amplify the gain of the motor neuron pool and enhance the fight-or-flight response. The amplified gain of the motor neuron pool can consequently exacerbate the amplitude of force fluctuations when the task is to maintain a force that must be constant and precise. Second, a stressor can disturb the sensory feedback from the muscle spindles onto the motor neuron pool by a stress-associated activation of gamma motor neurons via the sympathetic nervous system (17,18). Exposure to a stressor could activate both mechanisms.

The amount of visual feedback provided to the subject can also influence the force fluctuations during a steady contraction. Increased visual gain (pixels/N) about the force task reduces fluctuations in force, presumably due to modification of the descending command to the motor neuron pool (22,23,26). The experimental evidence of the interaction of age and visual feedback on precise motor performance appears to be mixed. For example, some studies suggest that visual feedback has no significant effect on force fluctuations during constant isometric contractions (3,25), whereas more recent studies suggest an improvement in force fluctuations for older adults when the visual feedback is removed (23,26,28).

The interaction between age, stressors, and visual feedback, therefore, can provide useful information about potential mechanisms that amplify the force fluctuations at low forces. The effects of a stressor on the interaction among age, sex, force variability (SD of force), stress hormones, and muscle activity have been published previously (4). The purpose of this study was to determine the effects of a stressor on the normalized force fluctuations and informa-
tion transmission exhibited by young, middle-aged, and old adults when a pinch-grip task was performed with and without visual feedback.

METHODS

Thirty-six adults (19–86 yr, 18 men and 18 women) volunteered to participate in this study. For most statistical comparisons subjects were assigned to a young (19–31 yr, N = 13), middle-aged (34–61 yr, N = 11), or old group (66–86 yr, N = 12). All subjects were assessed by a physician and were free from neurological impairments and were not using medications that are known to influence motor performance. In addition, all subjects were moderately active and had intact finger sensation. Subjects provided written informed consent before participation in the study and the human research committee at the University of Colorado in Boulder approved the procedures of the study. More detailed information about subject selection, experimental setup, and recordings other than force are provided in a previous report (4).

Experimental Setup

Each subject was seated and faced an oscilloscope that was located 0.5 m away at eye level. All subjects affirmed that they could see the oscilloscope display clearly. Both arms were abducted by 45° and the elbows were flexed by approximately 20°. Each forearm rested on the arm of the chair with the right forearm in a neutral position (halfway between forearm pronation and supination) and the left forearm pronated. The right hand and wrist were unsupported and subjects used the thumb and index fingers of the right hand to perform the pinch-grip task. The left hand was placed on the edge of the forearm support and remained relaxed throughout the experimental protocol. The electrical stimuli were delivered to the dorsal surface of the left hand.

Force Recordings

Subjects performed isometric contractions by pinching a force transducer (ATI Mini-40) with the thumb and index finger of the right hand. The force transducer (120 g) was 4 cm wide and had a sensitivity of 0.06 N·V⁻¹. Force output (sum of the thumb and index finger force) was sampled at 1 kHz with a 1401 Plus System (Cambridge Electronic Design, UK) and data were saved on a computer.

Experimental Procedures

Each subject reported to the laboratory twice. On the first visit, which lasted 30 min, subjects were familiarized with the environment and equipment, performed a maximal voluntary contraction (MVC) for the pinch-grip task, and practiced the submaximal pinch-grip task. On the second visit, which lasted 120 min and always occurred in the early afternoon, subjects participated in an experimental protocol that involved anticipatory (30 min), stressor (15 min), and recovery (25 min) periods. Subsequently, the threshold for the intensity of the electrical stimuli to be applied during the stressor period was determined. Once the 70-min protocol began, the force variability during the submaximal pinch-grip task was recorded nine times.

**MVC task.** Subjects were instructed to increase the force gradually from baseline to maximum over a 3-s period and to maintain the maximal force for about 2 s. Subjects began the task with two practice trials and then performed three trials when the force was recorded. Subsequent trials were performed if the difference in the peak forces for two of the trials were not within 5% of each other. The trial with the highest peak force was used for analysis and the MVC force was defined as the average force over the 0.5-s interval surrounding the peak.

**Submaximal pinch-grip task.** Each subject pinched the force transducer with the thumb and index finger of the right hand and was instructed to exert a pinch-grip force that matched a target line equal to 2% MVC force for 60 s (Fig. 1A). There were six 10-s oscilloscope sweeps for each pinch-grip trial. For the first 5 s of each sweep, the subject was able to view both the target line and force trace (visual-feedback condition), whereas for the last 5 s of each sweep, the subject viewed only the target line (no visual-feedback condition). Subjects were instructed to match the target force as accurately as possible and to maintain that force in the absence of visual feedback. The pinch-grip force was measured nine times during the 70-min protocol and the middle 40 s of each trial was used for analysis. Force fluctuations were calculated for the last 2.3 s of the visual-feedback segment and the first 2.3 s of no visual-feedback segment to minimize potential drifting of the force during the nonvisual-feedback condition. The 600 ms around the removal of the visual feedback was excluded from the analysis to limit any potential physiological adaptations by the subject knowing the visual-feedback condition was changing. For each trial, the mean force, normalized fluctuations in force, and information transmission were averaged across the intervals that corresponded to the four oscilloscope sweeps (Fig. 1).

**Noxious electrical stimuli.** Before beginning the experimental protocol, two carbon electrodes (2 × 2 cm) were attached to the dorsal surface of the left hand. The electrode leads were attached to a stimulator (Grass Instruments, Quincy, MA) that was used to deliver the electrical stimuli to the hand. For each subject, the amplitude of the electrical stimuli were 90–120 V above the minimal amount required to evoke a twitch response in the muscles on the dorsal surface of the left hand; stimulus intensity did not vary significantly with the age of the subject. The maximal voltage applied to the hand of any subject was 160 V. Subjects received a total of six shocks at 50–70 V above twitch (train duration was 200 ms and pulse duration was 100 ms) during the first bout of noxious electrical stimuli, 11 shocks at 65–85 V above twitch (train duration was 400 and pulse duration was 200 or 50 ms) during the second bout, and 13 shocks at 80–100 V above twitch (train and pulse duration was the same with bout 2) for the third bout.
Data Analysis

The dependent variables were the maximal force exerted with the pinch grip for the MVC task, the mean force (N), coefficient of variation (CV) for force (SD of force/mean force) \( \times 100\% \), information transmission (log2 (mean force/SD of force) \( \times 100\% \) bits) (23), and the power in the force spectrum from 0 to 12 Hz (bins of 1 Hz) for the submaximal pinch-grip task. The information transmission is based on information theory (21), which is often used as a theoretical construct to explain the influence of environmental events on human performance, and denotes the ratio of noise to information in a signal. In the current experiment, mean force was considered as the information transmitted and the CV of force was considered as the amplitude of noise. Force fluctuations were calculated from the detrended force data (see submaximal pinch-grip task paragraph above and Fig. 1A for more details) and were quantified as the highest value obtained from the different trials during the anticipatory, stressor, and recovery periods (e.g., average of middle four sweeps in trials 1, 4, and 3 in the anticipatory, stressor, and recovery periods, respectively). A Fourier analysis was performed on the force signal and autospectral analysis of the force signal was obtained using Welch’s averaged periodogram method with a nonoverlapping Hanning window (MATLAB 6.1). The length of the data segment was 2 s. The window size for the force signal, which was sampled at 1 kHz, was 1024, and the resolution was 0.976 Hz. For statistical comparisons, the frequency data were averaged over 1-Hz intervals for force (0–12 Hz; included >98% of the power in the total power spectrum density of the force signal). The dependent variables for the spectral analysis were the absolute and relative power (%) in the averaged bins.

Statistical Analysis

The dependent variables for the pinch grip task were compared with a mixed three-factor ANOVA (three age groups \( \times \) two visual conditions \( \times \) three periods) with repeated measures on visual conditions and periods (SPSS version 11.0). The power spectrum of force during the pinch-grip task was analyzed using a mixed four-factor ANOVA (three age groups \( \times \) two visual conditions \( \times \) three periods \( \times \) 11 frequency bins) with repeated measures on visual conditions, periods, and frequency bins. Multiple regression analyses were used to examine the contribution of each frequency bin from the power spectrum of force to the fluctuations in force and information transmission for each visual condition and protocol period. The alpha level for all statistical tests was set at 0.05 and paired contrasts (t-tests with Bonferroni corrections) were used to locate differences between the two vision conditions and periods when ANOVA yielded significant interactions. Data are indicated as mean \( \pm \) SD in the text and as mean \( \pm \) SEM in the figures.

RESULTS

The focus of this study was to examine the interaction of age, exposure to a stressor, and visual feedback on force fluctuations and information transmission.

Submaximal pinch-grip task. The maximal pinch-grip force did not differ among the age groups (young: 47.8 \( \pm \) 4.2 N; middle-aged: 47.4 \( \pm \) 5.2 N; old: 43.7 \( \pm \) 17.9 N; \( P > 0.1 \)). The mean force exerted by all subjects during the presence (0.93 \( \pm \) 0.35 N) and absence (0.92 \( \pm \) 0.36 N) of visual feedback was similar (\( P > 0.1 \)). Furthermore, mean force (0.92 \( \pm \) 0.35 N) did not vary during the experimental
protocol ($P > 0.1$). In contrast, the fluctuations in force increased significantly (period main effect; $P < 0.01$) and the information transmission decreased significantly (period main effect; $P < 0.01$) during the stressor period compared with the anticipatory and recovery periods for the visual- and no visual-feedback conditions and all age groups. Removal of visual feedback increased the fluctuations in force (Fig. 2A) and decreased the information transmission (Fig. 2B) only during the stressor period (vision × period interaction; $P < 0.01$). The force fluctuations increased (Fig. 3A; $P < 0.01$) and information transmission decreased (Fig. 3A; $P < 0.01$) with subject age, independent of visual-feedback condition (age × vision interaction; $P > 0.2$). Older adults exhibited greater force fluctuations (Fig. 4A; $P < 0.01$) and lower information transmission (Fig. 4B; $P < 0.01$) compared with young and middle-aged adults during all periods, and this finding was exacerbated during the stress period (age × period interaction; $P < 0.01$). Interestingly, middle-aged adults had higher force fluctuations and lower information transmission than young adults only during the stress period ($P < 0.01$).

Although the absence of visual feedback and age increased the fluctuations in force and reduced information transmission during the stressor period, the age × visual feedback interaction was not significant. To further explore the age × visual feedback interaction on force fluctuations and information transmission during the stressor, age was covaried as a function of visual feedback. This statistical design, which enhanced statistical power, indicated that the force fluctuations increased with age more during the stressor period in the absence of visual feedback ($P = 0.049$), but there was no effect on information transmission ($P = 0.1$).

**Force spectrum.** The median frequency for the force spectrum was $1.17 \pm 0.13$ Hz in the presence of visual feedback and $1.02 \pm 0.04$ Hz in the absence of visual feedback ($P > 0.1$). The total absolute power in the force spectrum, especially at 1–2 Hz, was greater during the stressor period compared with the other two periods ($P < 0.01$). Older adults exhibited greater power at frequencies ranging from 0 to 4 Hz and 5 to 9 Hz compared with young and middle-aged adults, especially during the stressor period (age × period × frequency interaction; $P < 0.01$; Fig. 5A). Middle-aged adults displayed greater power primarily from

**FIGURE 2**—The effects of visual feedback on the coefficient of variation of force (A) and information transmission (B) during the three experimental periods. Removal of visual feedback significantly increased the coefficient of variation for force and decreased information transmission only during the stressor period. The difference between the visual- and no visual-feedback conditions was not significant for the other two protocol periods.

**FIGURE 3**—The coefficient of variation of force (A) and information transmission (B) as a function of age. Although the age of the subject significantly increased the coefficient of variation of force and decreased information transmission, removal of visual feedback did not have a significant effect on either parameter. Each data point represents the average of the three experimental protocol periods.
were the dependent variables and the power in each frequency bin served as the independent variables. When the contractions were performed without any visual feedback, only modulation of power from 1 to 2 Hz \((r = 0.716)\) contributed significantly to the force fluctuations \((R^2 = 0.51; P < 0.001)\). Similarly, only modulation of power from 1 to 2 Hz \((r = 0.760)\) contributed significantly to the information transmission in the absence of visual feedback \((R^2 = 0.51; P < 0.001)\). In contrast, when the contractions were performed with visual feedback, the modulation of power from 1 to 2 Hz \((r = 0.545)\) and 6 to 7 Hz \((r = 0.2)\) contributed significantly to the force fluctuations \((R^2 = 0.41; P < 0.001)\). Finally, the modulation of power from 1 to 2 Hz \((r = 0.55)\) and 8 to 9 Hz \((r = 0.25)\) contributed significantly to information transmission with visual feedback \((R^2 = 0.42; P < 0.001)\). The observed force fluctuations and information transmission as a function of the predicted equations that are based on the power of the contributing frequencies are presented in Figure 6.

**DISCUSSION**

We have shown previously that noxious electrical stimuli can impair the ability of young, middle-aged, and, in particular, old adults to exert a constant force during a submaximal pinch grip (4). The focus of this study was to examine the effects of visual feedback on the impairments of fine motor performance that occur with exposure to a stressor. The novel finding was that removal of visual feedback exacerbated the effects of the stressor similarly in all age groups but did not influence the nonstressful periods of the protocol, that is, subjects exhibited amplified force fluctuations and lower information transmission when visual feedback was removed during the stressor period but not during the anticipatory or recovery periods. This finding suggests that exposure to a stressor can increase the synaptic input received by the motor neuron pool, but the effect of this input on the motor output can be attenuated by visual feedback.

**Stressor effects and visual feedback.** Although heightened levels of physiological arousal enhance the fight-or-flight response (12), they impair the ability of individuals to perform steady contractions due to an increase in the force fluctuations (4,15,16). As expected, the stressor amplified the force fluctuations in the current study and reduced the information transmission. Amplification of the force fluctuations during a stressor may be associated with enhanced monoaminergic drive or impaired sensory feedback to the motor neuron pool (12). The enhanced monoaminergic drive includes the secretion of neuromodulators from the brainstem to the motor neuron pool, which can augment the gain between the input received by the motor neuron pool and its output. Therefore, the output from the motor neuron pool during the presence of a stressor can be enhanced despite a similar input to the motor neurons, which can amplify the force fluctuations. Exposure to a stressor, furthermore, can also influence the synaptic input received by the motor neuron pool. For example, a major feature of the stress response is augmentation of sympa-
thetic nervous system activity, which can influence the sensitivity of the muscle spindles and hence the feedback transmitted by the associated afferents (17,18).

The findings of the current study indicate that visual feedback attenuated the force fluctuations and enhanced information transmission, but only during the stressor period. This effect was independent of age. Visual feedback did not have a significant effect on force fluctuations or information transmission during the anticipatory and recovery periods. This finding supports previous research that examined force variability in the quadriceps muscle group (3) and first dorsal interosseus muscle (25) and found no significant effects of visual feedback on force fluctuations. Other studies, however, suggest that increased visual feedback about the force task lowered the force fluctuations and amplified information transmission (22,23,28). The different findings may be due to two major methodological differences. First, in studies that show no significant effect of visual feedback on force fluctuations, subjects performed the contractions with (constant low visual gain) and without visual feedback, whereas in studies that show significant decrease in force fluctuations with visual feedback, subjects performed the contractions while the visual gain was varied, but not without any visual feedback. Second, in studies that show no significant effect of visual feedback on force fluctuations, subjects always achieved the target force with visual feedback and then visual feedback was removed, whereas subjects in the other set of studies achieved the target force initially with the amount of visual feedback (gain) that was tested for that trial. This method could alter both the descending command and afferent feedback to the motor neuron pool due to large corrections in force to achieve the task criterion. Overall, the above findings suggest that information transmission from afferent feedback in the absence of a stressor may be equally as effective as visual feedback in maintaining, rather than achieving, the target force.

The integration of visual feedback to minimize force fluctuations and maximize information transmission during constant isometric tasks, however, is illustrated by two findings of the current study. First, the presence of visual feedback attenuated the force fluctuations and enhanced information transmission only during the stressor period, which suggests that during the stressor the use of visual information influenced higher centers and consequently lowered the stress-induced enhancement of the synaptic input to the motor neuron pool. Second, the relative power in the force spectrum was different for the two visual conditions. In the absence of visual feedback, there was significantly greater relative power from 1 to 2 Hz and lower power at higher frequencies such as 2–3 Hz and 7–9 Hz compared with the spectrum for the visual-feedback condition. Furthermore, when visual feedback was removed, only modulation of power from 1 to 2 Hz contributed significantly to the force fluctuations and information transmission. In contrast, during the visual-feedback condition, force fluctuations were associated with modulation of power from 1 to 2 Hz and 6 to 7 Hz, whereas information transmission was associated with modulation of power in the force spectrum from 1 to 2 Hz and 8 to 9 Hz. These findings are similar to previous observations that indicate that integration of visual information about the fluctuations in force occur at about 6.5 Hz followed with corrections at about 1 Hz (22,23).

**Age, force fluctuations, and information transmission.** Old adults exhibited greater force fluctuations and reduced information transmission during all three periods of the protocol (anticipatory, stressor, and recovery)
compared with young and middle-aged adults. This difference, however, was most pronounced during the stressor period. Removal of visual feedback did not change the age-associated differences significantly, although there was a trend for exacerbating force fluctuations with age during the stressor period. The exacerbated response of the older adults during the stressor may be primarily due to impaired sensory feedback. There is evidence that sensory feedback from muscle spindles declines with advancing age (14) and older adults rely more on visual feedback than sensory feedback to execute accurate responses (19). Independent of the stressor effect, the age-associated difference was not influenced by the removal of the visual feedback, which supports previous research performed on the quadriceps muscle group (3). This result, however, contrasts recent findings that showed that removal of visual feedback improved force fluctuations in older adults (23,26,28). The improvements in force fluctuations by older adults when visual feedback is low can be explained with age-associated impairments in visual information transmission (23). Nonetheless, this would suggest that the afferent feedback from the muscle is similar between young and old adults, which contrasts the findings of this and other studies (14,19,20).

**Force fluctuations, information transmission and 1- to 2-Hz oscillations in force.** Most of the power in the force spectrum occurred at 1–2 Hz. Enhancement of the power at 1–2 Hz was associated with increased force fluctuations and decreased information transmission that depended on the stressor and the age of the subject. Numerous experimental studies have observed 1- to 2-Hz oscillations in force during isometric contractions performed against a rigid restraint (1,4,7,9,27); however, the exact origin of these oscillations in force is unknown.

There are at least three mechanisms that can explain the low-frequency oscillations in force. First, the coherent modulation of motor unit discharge at low frequencies (0–2 Hz) that accompanies the low-frequency oscillation in force is often presumed to reflect rhythmicities that are inherent in the descending drive onto the motor neuron pool (2,6,27). Second, the correlated output may be a consequence of intrinsic neuronal properties, such as active calcium conductances (10,11,24,29). Third, recent evidence suggests that approximately 80% of the low-frequency modulation in motor unit discharge (1–2.5 Hz) can be explained by the random variability in motor unit discharge, which may be the product of synaptic noise (5).

Findings from the current study support the hypothesis that modulation of force at 1–2 Hz may be associated with modulation of synaptic noise. Stressors and aging enhanced the CV of force but decreased information transmission. Although the strong negative association between CV of force and information transmission was expected due to the mathematical relationship of the two measures (CV of force is the inverse of the signal:noise), it provides evidence that, based on the concept of information theory (21), the CV of force can be considered as noise superimposed on a signal. The interesting finding, however, is the positive association between the CV of force and the 1- to 2-Hz oscillations in force. The CV of force during isometric contractions performed against a rigid restraint (1,4,7,9,27); however, the exact origin of these oscillations in force is unknown.
the task had been learned, however, a greater proportion of the energy in both the force and the motor unit spectra was focused on the imposed low-frequency modulation.

In summary, removal of visual feedback increased force fluctuations and reduced information transmission in all age groups during the stressor period, but had no effect on fine muscle performance during the anticipatory and recovery periods. In contrast, the stressor exacerbated the age-associated difference in force fluctuations and information transmission. Enhanced force oscillations from 1 to 2 Hz were associated with increased force fluctuations and reduced information transmission. These findings suggest that the stressor enhanced the synaptic input received by the motor neuron pool, but the influence of this input on the motor output can be attenuated by vision.

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