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Removal of Visual Feedback Lowers Structural Variability of Inter-Digit Force Coordination during Sustained Precision Pinch

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Abstract

This study examined the effects of visual feedback on inter-digit force coordination during precision pinch. Sixteen healthy, right-handed subjects were instructed to pinch an instrumented apparatus for 1 min with a stable force output. Visual feedback was provided for the first 30 s and withdrawn for the second 30 s. Detrended fluctuation analysis (DFA) and detrended cross-correlation analysis (DCCA) methods were used to quantify the time-dependent structures of each digit's force and of the force correlation between the digits. After removing visual feedback, the DFA scaling exponent, α_{DFA} , increased from 1.10 ± 0.12 to 1.29 ± 0.13 for the thumb and from 0.95 ± 0.08 to 1.33 ± 0.13 for the index finger ($F_{1,95}=372.47$, $p<0.001$); the DCCA scaling exponent, α_{DCCA} , increased from 1.00 ± 0.08 to 1.33 ± 0.13 ($t_{95}=20.33$, $p<0.001$). Structural changes were observed beginning with the first 5 s epoch after the removal of visual feedback. The results provide evidence that removing visual feedback lowers the structural variability of inter-digit force coordination. This change is reflected in the high-level control strategy, resulting in the two digits being more tightly coupled under somatosensory feedback without visual inputs.

Keywords

Sustained pinch; force variability; visual feedback; detrended fluctuation analysis (DFA); detrended cross-correlation analysis (DCCA)

Introduction

Stable object manipulation requires precise control of fingertip forces based on real-time visual and somatosensory feedback. This sensorimotor mechanism allows intricate coordination across digits to maintain the force output fluctuating around the required level [9]. These force fluctuations exhibit dynamic structures that vary with different feedback conditions [12, 16]. Investigating the variability of force control provides insight into the

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Contributions

KL and ZML designed the study, KL collected data and designed computer programs, KL, TLM and ZML analyzed and interpreted data, KL drafted manuscript, KL, TLM and ZML edited and revised manuscript, KL, TLM and ZML approved final version of manuscript.

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mechanisms of sensorimotor integration associated with neuromuscular function and central nervous processes.

Previous studies have reported that in a constant isometric contraction by a single digit, the visual feedback condition can influence the structural variability of the fingertip force. Visual display with increased intermittency or with increased visual-force gain raised the irregularity of the force structures [7, 8, 15], whereas completely withdrawing visual information reduced the force structure variations [1]. These findings demonstrate that digit force variability during a constant contraction is not fully determined by the activation of motor units in the peripheral nervous system, but also related to visuomotor modulation of the central nervous system [18].

In addition to single digit contraction, some studies have investigated the structural variability of force production during a precision pinch using the thumb and the index finger in children [4, 5] or patients with Parkinson's disease [20]. It was shown that with increased age from childhood to adulthood, more irregular structures were exhibited in the pinch force output [4, 5]. Additionally, the patients with Parkinson's disease produced a pinch force with higher irregularity than the healthy adults [20]. Although the force structural variability was examined under both visual and non-visual conditions in these studies, it remains unclear whether the absence of visual information alters the time-dependent structure of inter-digit force coordination during a sustained precision pinch. This issue involves the following two questions: First, does the removal of visual feedback alter the force structures of the thumb and the index finger as observed in single digit force tasks? Second, does the break of continuous visual modulation fortify or weaken the irregularity of force correlation between the digits? The investigation of these questions will aid in the understanding of how the central nervous system copes with altered sensory inputs while coordinating the engaged digits.

The purpose of this study was to investigate the role of visual feedback on inter-digit force coordination during sustained precision pinch. The time-dependent structure of each digit's force and that of the force correlation between the digits were examined before and after removing visual feedback. It was hypothesized that the variability of inter-digit force coordination would be lowered after the visual feedback loop was broken, which can be observed from decreased irregularity of individual digit force and simplified structure of force correlation.

Materials and methods

Subjects

Sixteen right-handed subjects (8 males and 8 females; 27.4 ± 4.1 years old), with no reported history of musculoskeletal or neurological disorders in their right hand or upper extremity, participated in this study. All subjects had normal or corrected -to-normal vision. Prior to experimentation, each subject signed a consent form approved by the Institutional Review Board.

Experimental set-up

The experimental set-up for the sustained pinching task is depicted in Figure 1a. A pinch apparatus was designed to measure fingertip forces at each digit-object interface using two transducers (Nano17, ATI Industrial Automation, Inc., Apex, NC). The resolution for each transducer was 0.025 N for the force direction perpendicular to the pinching surface. The signals were amplified and multiplexed using a custom ATI interface box (ATI Industrial Automation, Inc., Apex, NC) and converged to a 16-bit analog-digital converter (PXI-6289,

National Instrument, Austin, TX). The force signals were recorded simultaneously at a sampling frequency of 1000 Hz.

The pinch apparatus was rigidly fixed to a testing table a distance of 35 cm in front of the subject. The stabilized handle allowed for the investigation of pinch force coordination without mechanically dictated requirements for force/moment equilibrium while holding an otherwise freely moveable object. The apparatus was aligned with the subject's right shoulder and obliquely oriented approximately 45° with respect to each subject's sagittal plane. The pinching surfaces were covered with 100 grit sandpaper and were oriented in parallel with a pinch span of 20 mm. A 22-inch computer monitor, with a viewing area of 1024×1280 pixels, was positioned 50 cm in front of the subject (Figure 1a). Graphically displayed in the center of the screen was a tank with overall dimensions of 200 (width) × 500 (height) pixels. Along the vertical direction of the tank, a scale of 0–10 N was provided. The tank provided a bar of which the height fluctuated in real-time reflecting the average normal force exerted onto the pinch apparatus by the thumb and the index finger. A target line (1 pixel in width) at 5 N was also displayed on the tank. For the non-visual feedback condition, the target line and the bar depicting the real time force were not displayed. The visual feedback conditions and the data collection were implemented using a custom *LabVIEW* (National Instrument, Austin, TX) program.

Test procedures

Subjects sat comfortably in a height adjustable chair at the testing table. Their right upper arm was approximately abducted 0° in the frontal plane and flexed 30° in the sagittal plane. Their elbow was flexed approximately 90° and their forearm rested on a support and in a neutral pronation/supination position. Prior to starting the sustained pinch trials, the maximal voluntary contraction (MVC) of each subject's pinch capacity was evaluated.

Then, subjects were instructed to pinch the apparatus with the pulps of their thumb and index finger for 60 s. During the first 30 s, the computer monitor displayed the target line and the real-time force bar. Subjects were instructed to steadily maintain their pinch force to match as closely as possible the target line at 5 N. After 30 s, the visual information of the target line and the real-time force bar were removed and the subjects were instructed to maintain their prior force level for the remaining 30 s. Each subject performed six trials with two minutes of rest between trials to minimize muscle fatigue.

Data analysis

The digit forces exerted by the thumb and index finger from a representative subject are depicted in Figure 1b. The first 10 s of the data was excluded from data analyses. Each remaining signal was divided into three phases: (1) Phase I, with visual feedback (10–30 s); (2) Phase II, transition (30–40 s); and (3) Phase III, without visual feedback (40–60 s). Furthermore, the data from Phase I to Phase III (10–60 s) were divided into 10 consecutive 5s-epochs. It should be noted that visual feedback was removed at the end of epoch 4 (Figure 1b).

The structural variability of each individual digit's force was examined using detrended fluctuation analysis (DFA). Although a range of techniques are available, the validity and reliability of DFA in quantifying the time-dependent structures of nonstationary signals have been well examined [13]. According to the DFA algorithm, the time series of each force signal, $x(i)$, was first integrated as follows:

$$f_{DFA}(k) = \sum_{i=1}^k (x(i) - \overline{x(i)}), \quad (1)$$

where $\overline{x(i)}$ was the mean force. Then, the integrated force signal was divided into windows of equal length n ($n = 10$ to 1000). In each window, the local trend was $\sim$ estimated using a linear least-squares fit, $\tilde{f}_{DFA}(k)$. The root mean square, $F_{DFA}(n)$, was calculated over the window of length n .

$$F_{DFA}(n) = \sqrt{\frac{1}{n} \sum_{k=1}^n [f_{DFA}(k) - \tilde{f}_{DFA}(k)]^2} \quad (2)$$

The scaling exponent, α_{DFA} , is the slope of the $\log(n)$ vs. $\log F_{DFA}(n)$ plot and reflects the long-range auto-correlation of the time series. α_{DFA} values of 0.5, 1, and 1.5 indicate the original time series' correspondence to white, pink and Brown noise, respectively. An α_{DFA} value between 0.5 and 1 indicates a persistent long-range power-law correlation, whereas an α_{DFA} between 1 and 1.5 indicates a high correlation without power law [13].

Detrended cross-correlation analysis (DCCA) was applied to examine the time-dependent structure of the force correlation between the digits. DCCA is a method to detect long-range cross-correlation between two simultaneously recorded time series signals with robustness against noise, data length, and non-stationarity [14, 21]. Using the DCCA algorithm, the forces of the thumb and index finger were integrated and then the covariance between the integrated signals was calculated. This covariance was divided into $N-n$ overlapping windows, where N is the data length of each time series and n is the windows size. Within each window, a linear least-squares fit was determined and the covariance of the residuals for each n was calculated as follows:

$$f_{DCCA}^2(n, i) = \frac{1}{n-1} \sum_{k=i}^{i+n} (R_k - \tilde{R}_{k,j})(R'_k - \tilde{R}'_{k,j}), \quad (3)$$

where R_k and R'_k are the integrated forces of the thumb and the index finger, respectively, and $\tilde{R}_{k,j}$ and $\tilde{R}'_{k,j}$ are the local trends of R_k and R'_k . The detrended covariance $F_{DCCA}(n)$ was calculated by averaging the covariance over all windows.

$$F_{DCCA}(n) = \sqrt{\frac{1}{N-n} \sum_{i=1}^{N-n} f_{DCCA}^2(n, i)} \quad (4)$$

The scaling exponent, α_{DCCA} , is the slope of the $\log(n)$ vs. $\log F_{DCCA}(n)$ plot and is an indication of the long-range cross-correlation between the forces exerted by the thumb and the index finger.

Both DFA and DCCA were applied to the fingertip forces for Phase I and Phase III. Additionally, these algorithms were used to examine the effect of time on the short-term structural variability in successive 5s-epochs from Phase I to Phase III (10–60 s, Figure 1b) for each single digit's force and for the force correlation between the digits.

Statistical analyses

Statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL). The mean and standard deviation of the force exerted by each individual digit was calculated for the conditions of with and without visual feedback (i.e. Phase I and Phase III). The normality of α_{DFA} and α_{DCCA} was verified using the Kolmogorov-Smirnov test. A two-way repeated measures ANOVA (2×2) was performed on α_{DFA} to evaluate the effects of digit (thumb or index finger) and of visual feedback condition (with or without visual feedback). A paired t -

test was used to examine the effects of visual feedback on α_{DCCA} . A two-way repeated measures ANOVA (10 epochs $\times$ 2 digits) was applied to examine the effects of time and digit on α_{DFA} . A one-way repeated measure ANOVA (within-subject factor: 10 epochs) was applied to examine the time effects on the α_{DCCA} . The Huynh-Feldt correction was used when the assumption of sphericity was violated. Post hoc pairwise comparisons were analyzed using Least Significant Difference tests. A surrogate test was performed to ensure the changes of α_{DCCA} did not merely reflect the altered auto-correlation of each digit force. Differences between the α_{DCCA} calculated from the original signals and those calculated from the surrogate signals (100 surrogate datasets generated from the force outputs of each trial with and without visual feedback, respectively) were examined by hypothesis testing (95% confidence interval). A p -value of less than 0.05 was considered statistically significant.

Results

The MVC was found to be 74.7 ± 13.3 N for male subjects and 45.4 ± 7.8 N for female subjects. During the sustained pinch trials, the average force magnitude of the thumb and index finger decreased from 4.9 ± 0.2 N with visual feedback to 4.7 ± 0.6 N without visual feedback ($t_{95}=2.56$, $p=0.012$).

The α_{DFA} values of both digits significantly increased after removing visual feedback ($F_{1,95}=372.47$, $p<0.001$; Figure 2a). An interaction was found between the digit and the visual feedback condition ($F_{1,95}=142.08$, $p<0.001$). The α_{DFA} of the thumb ($\alpha_{DFA}=1.10 \pm 0.12$) was significantly higher than that of the index finger ($\alpha_{DFA}=0.95 \pm 0.08$) with visual feedback ($p<0.001$). However, without visual feedback, α_{DFA} of the thumb ($\alpha_{DFA}=1.29 \pm 0.13$) was less than that of the index finger ($\alpha_{DFA}=1.33 \pm 0.13$, $p<0.001$). Visual feedback also significantly affected α_{DCCA} . The α_{DCCA} value changed from 1.00 ± 0.08 during Phase I to 1.33 ± 0.13 during Phase III ($t_{95}=20.33$, $p<0.001$, Figure 2b). The surrogate test confirmed that the dynamical information provided by the DCCA was not merely a reflection of the auto-correlation functions of force signals.

A significant time effect was observed in α_{DFA} across the 10 epochs ($F_{8,788}=24.83$, $p<0.001$, Figure 3a). Post hoc analysis showed that the α_{DFA} of the epochs after removing visual feedback (epoch 5–10) was significantly higher than any of the epochs with visual feedback (epoch 1–4, $p<0.001$). No significant difference was observed in α_{DFA} within the same feedback condition. A significant interaction between the digits and the epochs was observed in α_{DFA} ($F_{9,855}=5.50$, $p<0.001$). With visual feedback, the α_{DFA} of the thumb was lower than that of the index finger only in epoch 1 (10–15 s, $p<0.001$). By contrast, when no visual feedback was provided the α_{DFA} values of the index finger were significantly higher than those of the thumb for all epochs (epochs 5–10, 30–60 s, $p<0.001$).

Similarly, a significant time effect was observed in α_{DCCA} across the 10 epochs ($F_{8,795}=22.87$, $p<0.001$, Figure 3b). Post hoc analysis showed that the α_{DCCA} of epochs 5 to 10 were significantly higher than that of epochs 1 to 4 ($p<0.001$). No significant difference of α_{DCCA} was observed within epochs 1–4 or within epochs 5–10.

Discussion

This study examined the effects of visual feedback on the inter-digit force coordination during a sustained precision pinch. The results of DFA and DCCA demonstrated that the absence of visual feedback reduced the structural variability of each individual digit's force and that of the force correlation between the digits. This reduced force variability reflects a decreased flexibility in control of each digit's force; the simplified structure of the force

correlation shows that the two digits were more tightly coupled. Both of these findings contribute to a decreased structural variability of inter-digit force coordination after the removal of visual feedback. These findings have implications related to understanding the motor control mechanisms involved with different feedback modalities.

The structural changes of each digit's force are consistent with the notion that visual feedback can alter the time-dependent properties of force variability during a sustained contraction by a single digit [1, 8, 16]. For example, more irregular force structure patterns have been observed during index finger pressing when visual information was provided, compared to when visual feedback was withdrawn [1]. The higher irregularity of digit force under the visual condition is probably attributable to the visual-guided force correction; whereas in absence of this visuomotor correction, the central nervous system exerts a smoother muscle contraction [1, 2]. In accordance with these findings, the current study further revealed that visuomotor correction can mediate the force structures for all the digits involved for a pinch.

Moreover, statistical interactions between the digits and the feedback conditions were found in this study. In the presence of visual feedback, the index finger force showed a higher structural variability (lower α_{DFA}) than that of the thumb; after removing visual feedback, the force structure of the index finger showed lower variability than that of the thumb (Figure 2a). These results suggest that for a sustained precision pinch with visuomotor correction, the index finger showed a more flexible force control than the thumb; but without this correction, the index finger presented lower force flexibility than the thumb. The force flexibility of the thumb and index finger was able to be separately modulated by the central nervous system in accordance with the feedback conditions. This supports the theory that independent neural networks are responsible for adjustments of fingertip forces exerted by each engaged digit during manipulation [3].

The results of DCCA indicated that the time-dependent structure of inter-digit force correlation changed from a pink noise pattern ($\alpha_{DCCA} = 1.00 \pm 0.08$) under the visual feedback condition towards a Brown noise pattern ($\alpha_{DCCA} = 1.33 \pm 0.13$) under the non-visual feedback condition (Figure 2b). This pink-to-Brown noise transition indicates less irregular patterns in the structure of the force correlation, reflecting a lowered dynamical degree of freedom after the removal of visual feedback [10, 11]. Different from mechanical degrees of freedom, the dynamical degrees of freedom specifies the dimension of the motor system in state space, reflecting the irregularity of the motor behavior [11]. The change of the dynamical degrees of freedom under different feedback conditions is possibly due to a higher level sensory-based control in the central nervous system that supports the spatiotemporal coordination of both digits [3]. Under visual feedback, the central processes integrate visual, tactile, and proprioceptive information into a close-loop feedback control [19]. This feedback control allows the two-digit motor system to coordinate flexibly (with a higher degree of freedom) in order to minimize the overall error of the force output. By contrast, the withdrawal of visual information transfers the high-level control mechanism to somatosensory feedback dominated by tactile and proprioceptive information [16]. This new mechanism, therefore, leads to a stronger coupling of the engaged digits during pinch by decreasing the dynamical degrees of freedom of the motor system [6].

The examination of the short-term fluctuations in consecutive 5s-epochs (Figure 3a and 4b) further indicated that the onset of significant structural change of the inter-digit force coordination occurred in the first epoch after removing visual feedback (25–30 s). This observation suggests that the transition from the visual to the non-visual control mechanism was completed within 5 s after removing visual feedback. It should be noted that this structural change over time is not equated with the continuous decline of force magnitudes

in the absence of visual feedback [19]. This difference supports that the amount and the structure of force variability at low force levels are controlled by separate processes [17]. In this study, although muscle fatigue cannot be ruled out, the effect of fatigue should have been inconsequential under the low pinch force. The results that within a given feedback condition the structural variability did not change over time as in a typical force curve associated with fatigue further suggest that muscle fatigue in this study unlikely played a role in the inter-digit force coordination. Also, it has been found that the force structural variability is not altered by the magnitude of the force output if it is within 20% MVC [17]. Considering the pinch force in this study was 5.2–16.4% MVC across all the subjects, the difference in subjects' pinch strength should not be a significant factor that influences the force structural changes. Consequently, the central control mechanism, rather than the peripheral muscle function, accounts for the lowered structural variability of the inter-digit force coordination after removing visual feedback.

Conclusions

This study found that the removal of visual feedback lowers the structural variability of inter-digit force coordination during a sustained pinch. The central processes mediated both the structures of the individual digit's force and the structure of the force correlation in accordance with sensory feedback conditions. The transition from the visual to the non-visual control mechanism was completed within 5 s after withdrawing visual feedback. The results of this study indicate a lowered dynamical degrees of freedom for the motor system in the absence of visual feedback, leading to a more tightly coupled inter-digit force coordination under somatosensory feedback.

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Highlights

- Each digit produced force with simplified structure after removing visual feedback
- Without visual feedback, force correlation showed reduced structural variability
- Removal of visual feedback lowered variability of inter-digit force coordination

Figure 1. Experimental setup and force output from a representative subject

(a) Experimental setup. The yellow bar shows the real-time grip force and the target is displayed in the middle of the tank at 5 N. The close-up view depicts the pinch apparatus and the pinching posture. (b) Force output from a representative subject. The first 10 s (0–10 s) were excluded from data analysis. Visual feedback was removed at 30 s. The forces exerted by the thumb and index finger were divided into three phases: Phase I (10–30 s) is with visual feedback; Phase II (30–40 s) is the transitional period after removing visual feedback; and Phase III (40–60 s) is without visual feedback (the contrasting period to Phase I). From Phase I to Phase III (10–60 s), data were equally divided as 10 consecutive 5s-epochs. By this partition, epoch 4 (25–30 s) was the last epoch under the visual condition, whereas epoch 5 (30–35 s) is the first epoch under the non-visual condition.

Figure 2. Effects of visual feedback on the structural variability of digit force and that of force correlation between digits
 (a) Mean and standard deviation of α_{DFA} for the isometric force of the thumb and index finger with and without visual feedback; (b) Mean and standard deviation of α_{DCCA} with and without visual feedback. * indicates significant difference at $p < 0.001$

Figure 3. Time effects of short-term structural variability of digit force and that of force correlation between digits

(a) Mean and standard deviation of the α_{DFA} for the thumb and the index finger; (b) Mean and standard deviation of the α_{DCCA} . Time is represented as 5s-epochs from 10–60 s. * indicates a significant difference between the thumb and the index finger ($p < 0.001$); † indicates a significant difference from the previous epoch ($p < 0.001$).