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Research article

Coherence and interlimb force control: Effects of visual gain

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ABSTRACT

Neural coupling across hemispheres and homologous muscles often appears during bimanual motor control. Force coupling in a specific frequency domain may indicate specific bimanual force coordination patterns. This study investigated coherence on pairs of bimanual isometric index finger force while manipulating visual gain and task asymmetry conditions. We used two visual gain conditions (low and high gain = 8 and 512 pixels/N), and created task asymmetry by manipulating coefficient ratios imposed on the left and right index finger forces (0.4:1.6; 1:1; 1.6:0.4, respectively). Unequal coefficient ratios required different contributions from each hand to the bimanual force task resulting in force asymmetry. Fourteen healthy young adults performed bimanual isometric force control at 20% of their maximal level of the summed force of both fingers. We quantified peak coherence and relative phase angle between hands at 0–4, 4–8, and 8–12 Hz, and estimated a signal-to-noise ratio of bimanual forces. The findings revealed higher peak coherence and relative phase angle at 0–4 Hz than at 4–8 and 8–12 Hz for both visual gain conditions. Further, peak coherence and relative phase angle values at 0–4 Hz were larger at the high gain than at the low gain. At the high gain, higher peak coherence at 0–4 Hz collapsed across task asymmetry conditions significantly predicted greater signal-to-noise ratio. These findings indicate that a greater level of visual information facilitates bimanual force coupling at a specific frequency range related to sensorimotor processing.

1. Introduction

Executing isometric force control involves producing accurate force outputs around a submaximal target level while processing online somatosensory feedback [5]. In particular, during bimanual force control, well-coordinated and interactive interlimb behaviors are responsible for successful modulation of resultant forces produced by two hands. Previous researchers hypothesized that neural synchrony in brain activity between hemispheres (e.g., EEG–EEG coherence) and homologous muscle activity between two limbs (e.g., EMG–EMG coherence) contributes to controlling and coordinating bimanual force [4,9]. Specifically, the EEG–EEG coherence across the primary motor cortices at the alpha frequency band (4–12 Hz) was reduced in bimanual force control as compared to unilateral force control [18], whereas the EMG–EMG coherence across two homologous hand muscles at the alpha frequency band increased when forces were highly coordinated [6,22]. Despite the evidence of altered neuromuscular coupling underlying the strength of bimanual coordination [8,30], the exact nature of the coupling remains unclear as to how force signals from two hands are synchronized at specific frequency ranges during bimanual force control.

Isometric forces produced by unimanual hands can be characterized by frequency properties. For example, force power in 0–4 Hz was related to sensorimotor feedback processes and force power up to 12 Hz was associated with reflective and faster feedforward processes [21,28]. These findings indicated that coherence at a specific frequency range may vary with the characteristics of bimanual force control tasks. In fact, earlier studies reported altered interlimb coordination by investigating peak coherence on force signals at a specific frequency based on different target force levels [10,20]. During bimanual index finger force control, peak coherence at 0–5 Hz was higher as targeted force level was elevated, whereas no changes in peak coherence occurred at 8–12 Hz. Interestingly, recent findings revealed that high visual gain and symmetric task coefficients imposed on both hands improved bimanual force coordination (i.e., more negative correlation) [3,14]. These findings support a proposition that peak coherence at a specific frequency band is presumably altered by visual gain and task asymmetry conditions. If the proposition is correct, then the value of peak coherence as an index of coordination may be associated with bimanual force control.

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Thus, we investigated peak coherence of bimanual force signals while participants bimanually performed isometric index finger force control at 20% of their maximal level of the summed force of both fingers. Further, we manipulated visual gain and task asymmetry between hands: (a) visual gain (low and high gain = 8 and 512 pixels/N) and (b) task coefficient ratios imposed on the left and right index finger forces (0.4:1.6; 1:1; 1.6:0.4, respectively). Participants tried to match the weighted sum of individual finger forces to the target. Unequal coefficient ratios essentially caused different contributions from each hand to total bimanual force resulting in force asymmetry [11]. Given that visuomotor processing during force control was highly associated with force oscillation below 4 Hz [29], we hypothesized that peak coherence at 0–4 Hz was higher at high gain when two hands produced symmetrical forces. Further, we expected that a larger peak coherence at 0–4 Hz would relate to improved bimanual force control.

2. Methods

2.1. Participants

Fourteen healthy young adults (7 females and 7 males; mean ± SD age = 25.6 ± 5.9 years; 14 right-handed) with no history of musculoskeletal or neurological deficits in their upper extremities volunteered. All participants read and signed an informed consent approved by the University of Florida's the Institutional Review Board prior to testing.

2.2. Apparatus

Consistent with earlier experiments [3,10], volunteers executed an abduction task with their two index fingers in bimanual isometric force control at 20% of MVC. Participants sat 78 cm away from a 43.2 cm LCD monitor (1024 × 768 pixels; 100 Hz refresh rate) and placed their left and right arms on the table with comfortable positions (shoulder flexion = 15–20° and elbow flexion = 20–40°). Setting the left and right hands in a prone position, each index finger was extended and the distal phalange of the index fingers contacted two separate force transducers (MLP-25; Transducer Techniques; 4.16 × 1.27 × 1.90 cm, range = 111.2 N, 0.1% sensitivity). To prevent involvement of the wrist and the three other fingers during movements, the forearms and three fingers were strapped in stationary positions.

A 15LT Grass Technologies Physio-data Amplifier System (AstroMed Inc.; an excitation voltage of 10 V and a gain of 200) amplified force signals. The force signals were collected at the sampling rate of 100 Hz using a 16-bit analog-to-digital converter (A/D; NI cDAQ–9172 + NI 9215, force unit detected minimally 0.0016 N). A custom LabVIEW Program (National Instruments, Austin, USA) manipulated visual gain and task coefficient conditions, and we used a custom Matlab Program (Math Works™ Inc., Natick, USA) for offline analyses.

2.3. Experimental procedures

We administered three MVC trials and 54 bimanual force control trials. For the MVC and bimanual force control trials, participants were required to simultaneously abduct their two index fingers against the force transducers. Before testing started, three MVC trials (each trial = 6 s) were administered with participants instructed to generate maximum bimanual index finger abduction force summed for both hands. The mean summed force of both index fingers across three MVC trials was used for determining each individual's target level (i.e., 20% of mean of three MVC values). During the 15 s experimental trials, the target level was displayed as a green line to which participants attempted to match their summed output (white line).

We manipulated two task conditions: (a) the amount of visual information: low vs. high gain and (b) task asymmetry: left-biased vs. equal vs. right-biased. Varying the spatial resolution of visual information created two visual gain conditions: low and high gain = 8 and 512 pixels/N. Greater visual gain increases spatial resolution of visual information [17]. Further, task asymmetry was varied via instructions that imposed task coefficients between the left and right finger forces: (a) left hand biased = 1.6:0.4; (b) equal (no bias) = 1:1; and (c) right hand biased = 0.4:1.6 [14]. Under these conditions, participants tried to match their weighted sum of finger forces to the targeted level. Unequal task coefficients caused a force asymmetry between constrained hands (the force output of one hand multiplied by 1.6 and the other hand multiplied by 0.4). Thus, the relative contribution of each finger's actual force to total force is changed in the unequal task coefficient conditions (left-biased and right-biased) [11]. Participants completed 6 blocks (i.e., 2 × 3; Visual Gain × Task Asymmetry). Before each block, participants received the coefficients imposed on each finger force, and completed 4 practice trials. Then, we administered 9 experimental trials for six blocks totaling 54 trials (1 trial = 15 s). Rest periods included 10 s rest between trials and 60 s rest between blocks.

2.4. Data analyses

Consistent with previous studies [14,15], force data were filtered by a bidirectional fourth-order Butterworth filter at 30 Hz of cut off frequency. Further, we eliminated the first 5 s and final 1 s to minimize the transient force control effects of an initial adjustment and early-termination. Thus, the offline analyses focused on the middle 9 s of each trial.

For estimating the strength of interlimb coordination, we analyzed coherence between force outputs from the two hands [10,20] using magnitude-squared coherence. This coherence analysis can quantify the cross-correlation between pairs of force signals within a trial at each frequency of signal. The coherence values ranged from 0 to 1, and values close to 1 indicated a high correlation between the two hands at each frequency indicating better interlimb coordination patterns. Using Formula (1), we computed coherence between the two forces for each trial with a window length of 100 points and frequency resolution of 0.11 Hz [16].

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \tag{1}$$

Where x is left force signals and y is right force signals. P_{xy} (*f*) is the cross-spectral density between left and right force signals. P_{xx} (*f*) and P_{yy} (*f*) are the autospectral density of left and right force signals respectively.

Changes in coherence as a function of visual gain and task asymmetry conditions were determined by calculating peak coherence in three frequency bands: (a) 0–4 Hz (0 ~ 3.95 Hz), (b) 4–8 Hz (3.96 ~ 7.91 Hz), and (c) 8–12 Hz (7.92 ~ 11.99 Hz) [24].

In addition, to determine phase differences between two hands (i.e., in-phase and anti-phase) at specific frequency domains, we used a cross power spectral density analysis [2]. Given that we allowed participants the freedom of initiating finger-forces, we rectified raw phase angle values (−180° ~ 180°) so that the range of relative phase angle in this analysis was equal to 0°–180°. The relative phase angle close to 0° indicated in-phase between hands whereas the relative phase angle close to 180° denoted anti-phase between hands at a certain frequency band. Consistent with our coherence analysis, we calculated peak relative phase angle in three frequency bands (0–4, 4–8, and 8–12 Hz).

To estimate bimanual force control performance, we quantified information transmission by examining the signal-to-noise ratio (i.e., mean force/SD of force) for each trial [26]. Moreover, we calculated force asymmetry between two hands in two different ways: (a) weighted force asymmetry = weighted left force (actual left mean force × weighted task coefficient)/weighted right force (actual right mean force × weighted task coefficient) and (b) actual force asymmetry = actual left mean force/actual right mean force. For example, in