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Abstract

The purpose of this study was to determine whether altered interlimb coordination patterns across trials improved bimanual force control capabilities within a trial. Fourteen healthy young participants completed bimanual force control tasks at 5%, 25%, and 50% of maximum voluntary contraction with and without visual feedback. To estimate synergetic coordination patterns between hands across multiple trials, we analyzed our primary outcome measure by performing an uncontrolled manifold analysis. In addition, we calculated force accuracy, variability, and regularity within a trial to quantify task stabilization. Using Pearson's correlation analyses, we determined the relation between the changes in bilateral motor synergies (i.e., a proportion of good variability relative to bad variability) and bimanual force control performance from no-vision to vision conditions. The findings revealed that the presence of visual feedback significantly increased bilateral motor synergies with a reduction of bad variability components across multiple trials, and decreased force error, variability, and regularity within a trial. Further, we observed significant positive correlations between higher bilateral motor synergies and increased improvements in force control capabilities. These findings suggested that bimanual synergetic coordination behaviors at the planning level modulated by external sensory feedback may be related to advanced task stabilization patterns at the execution level.

Introduction

Bimanual force control is frequently involved in conducting various activities of daily living[1]. Moreover, successful interlimb force coordination contributes to accomplishing the goals of bimanual movements[2]. Conventional perspectives on bimanual force coordination assume that force outputs from each hand need to be coupled such as a single unit so that these coupling patterns improve bimanual force control performance[3]. However, recent studies raised a proposition that two hands consistently interact and compensate each other in motor synergies to stabilize task performance. The reason being that the central nervous system tends to select the synergetic movements in numerous options (i.e., motor abundance) rather than attempting to find a specific method (i.e., motor redundancy)[4,5].

The uncontrolled manifold (UCM) analysis is frequently used for estimating individual's motor synergetic patterns between two limbs[4,6]. Given that the UCM findings mainly focus on changes in motor control patterns across multiple trials, this approach provides an elegant way to explore movement variability and compensatory behaviors in the motor system at the planning levels[7,8]. The UCM analysis quantifies the proportion between the variance of fundamental elements projected to the UCM line (i.e., good variability that has no effect on task performance) and those projected to the orthogonal (ORT) line (i.e., bad variability that interferes with task performance). Thus, a higher proportion of good variability relative to bad variability indicates greater synergic force outputs produced by the two hands across different trials. Importantly, the increased synergic forces may contribute to the stabilization of overall task performances.

Several UCM studies examined changes in interlimb force coordination patterns (i.e., bilateral motor synergies) across multiple bimanual force control trials according to specific constraints (i.e., organism, task, and environment constraints) that may influence an individual's coordination functions[9-11]. For example, findings from studies on elderly people and individuals post stroke revealed less bilateral motor synergies with higher task error and variability within a trial as compared with age-matched controls because of their potential organism constraints such as impaired sensorimotor processing[10,12,13]. Moreover, the asymmetrical task goals during bimanual force control increased bilateral motor synergies with more precise force control in healthy young adults in comparison to the symmetrical force production tasks[6,9,11]. Although these findings indicated that certain constraints may simultaneously influence levels of bilateral motor synergies across multiple trials and force control capabilities within a trial, whether specific changes in motor synergic patterns are directly related to an altered state of overall task stabilization in the motor system is still unclear.

To determine the relationship between bilateral motor synergies and task stabilization, we modulated visual information during bimanual force control tasks. Previous findings reported that the presence of visual information improved force accuracy, variability, and regularity with better force coordination function (e.g., more negative correlation between two hands) within a trial, whereas the absence of visual information impaired the force control capabilities and facilitated more positive correlation patterns[14,15]. Further, some studies reported that the modulation of visual information strongly affected individual's motor control strategies using higher cognitive functions as indicated by altered motor synergic patterns across multiple trials[16,17].

Thus, the purpose of this study was to examine altered bilateral motor synergies across multiple trials and force control capabilities within a trial for healthy young adults while manipulating vision and no-vision conditions. Further, we determined whether changes in bilateral motor synergies were related to task stabilization during bimanual force control tasks. Participants executed movements associated with three different targeted force levels (i.e., 5%, 25%, and 50% of maximum voluntary contraction: MVC) because an individual's motor control strategies across trials and within a trial may be influenced by different task difficulty[18-20]. Given that the positive effects of visual information on motor control capabilities[21], we hypothesized that from no-vision to vision conditions the participants would increase bilateral motor synergies and improve force control capabilities, and further the increase in bilateral motor synergies would be related to more improvements in task stabilization.

Results

UCM findings: bilateral motor synergies, good variability, and bad variability

Repeated measures ANOVA on the Visual Condition × Force Level (2 × 3) design for the V_{Index} showed a significant Vision Condition main effect [F (1, 13) = 211.585; $P < 0.001$; partial $\eta^2 = 0.942$; Fig. 1A]. Post-hoc analysis revealed that the values of V_{Index} were significantly greater in the vision condition than those in the no-vision condition collapsed across three targeted force levels. Two-way repeated measures ANOVA on the V_{UCM} demonstrated a significant Force Level main effects [F (1.042, 13.549) = 19.045; $P = 0.001$; partial $\eta^2 = 0.594$; Fig. 1B]. The post-hoc analysis showed higher values of the V_{UCM} at 5% of MVC than those at 25% of MVC ($P = 0.002$) and 50% of MVC ($P = 0.002$).

The analysis on the V_{ORT} revealed a significant Vision × Force level interaction [F (2, 26) = 4.078; $P = 0.029$; partial $\eta^2 = 0.239$; Fig. 1C]. The post-hoc analyses indicated that the values of V_{ORT} were significantly less in the vision condition than those in the no-vision condition at 5% of MVC ($P < 0.001$) and 50% of MVC ($P < 0.001$). At 25% of MVC, the analysis similarly showed different trends in the V_{ORT} between vision and no-vision conditions ($P = 0.051$). These findings indicate that interlimb coordination across multiple trials as indicated by bilateral motor synergies was improved when visual feedback was available, and further the presence of visual feedback reduced bad variability components in bilateral motor synergies. These patterns were observed across all targeted force levels.

Insert Figure 1 about here

Bimanual motor performance findings: force accuracy, variability, and regularity

Repeated measures ANOVA on the two-way Visual Condition × Force Level (2 × 3) for the RMSE revealed a significant Vision × Force level interaction [F (1.328, 17.261) = 27.193; $P < 0.001$; partial $\eta^2 = 0.677$; Fig. 2A]. The post-hoc analyses revealed that the values of RMSE were significantly less in the vision condition than those in the no-vision condition across the three targeted force levels ($P < 0.001$). Further, in the no-vision condition, the values of RMSE significantly increased as the force level elevated ($P < 0.001$).

A two-way repeated ANOVA on the CV showed two significant main effects: (a) Vision Condition [F (1, 13) = 61.273; $P < 0.001$; partial $\eta^2 = 0.825$; Fig. 2B] and (b) Force Level [F (1.157, 15.045) = 5.594; $P = 0.028$; partial $\eta^2 = 0.301$]. The post-hoc analysis on the Vision Condition main effect revealed less CV in the vision condition than those in the no-vision condition. Additional post-hoc analysis on the Force Level main effect showed higher CV at the 5% of MVC ($M \pm SE$ = 5.61±0.65%) than those at the 25% of MVC ($M \pm SE$ = 3.54±0.28%; $P = 0.020$).

Analysis of the SampEn revealed a significant Vision × Force Level interaction [F (2, 26) = 5.162; $P = 0.013$; partial $\eta^2 = 0.284$; Fig. 2C]. The follow-up tests showed higher SampEn in the vision condition than those in the no-vision conditions across the three targeted force levels ($P < 0.001$). Further, for both visual conditions SampEn decreased as the targeted force level increased ($P < 0.001$). Taken together, these findings indicate that the presence of visual feedback efficiently improved bimanual force control performances within a trial, as indicated by less force error, variability, and regularity regardless of different targeted force levels.

Insert Figure 2 about here

Correlation findings: bilateral synergies versus force control performance

To determine whether changes in interlimb coordination patterns across multiple trials (i.e., bilateral motor synergies) were related to changes in bimanual force control performances (i.e., force accuracy, variability, and regularity) within a trial from the no-vision to vision conditions, we performed Pearson's correlation analyses. Given that the positive effects of visual feedback on bilateral motor synergies and force control performances similarly appeared across different targeted force levels, we analyzed the correlation patterns including the findings from the three targeted force levels. The correlation findings showed that greater changes in the V_{Index} from the no-vision to vision conditions were significantly related to an increased reduction in the CV collapsed across the three targeted force levels (Fig. 3A). Moreover, increased values of the V_{Index} with visual feedback were significantly related to higher values of SampEn collapsed across the three targeted force levels (Fig. 3B). However, the analysis failed to show a significant correlation between the V_{Index} and RMSE (r = -0.138; P = 0.385). These findings indicate that advanced interlimb coordination patterns across multiple trials were related to increased improvements in bimanual force control performances within a trial.

Insert Figure 3 about here

Discussions

The purpose was to determine the effect of two visual conditions and three targeted force levels on bilateral motor synergies and force control performances during isometric force control tasks in healthy young adults. One of our leading questions involved whether altered interlimb coordination patterns across trials improved bimanual force control capabilities within a trial. Additionally, we examined the correlation between changes in bilateral motor synergies and force control performances to specify whether selecting optimal bimanual coordinative motor solutions across multiple trials was related to successful task stabilization within a trial. The combined findings revealed that in the vision condition the performers significantly increased bilateral motor synergies while reducing bad variability across multiple trials. Moreover, the presence of visual feedback significantly improved bimanual force control performances within a single trial, as indicated by higher force accuracy, less force variability, and greater force irregularity. Importantly, we observed significant correlations between an increase in bilateral motor synergy and improvements in force control performances from no-vision to vision conditions collapsed across the three targeted force levels.

The UCM findings revealed that the values of bilateral motor synergies between two hands significantly increased from no-vision to vision condition with a reduction of bad variability components across the three targeted force levels. According to Newell's constraints theory[34,35], cooperative bimanual movement patterns in the motor system were primarily dependent on three constraints within a single trial: (a) organism constraints (e.g., a performer's capability), (b) environmental constraints (e.g., extrinsic feedback), and (c) task constraints (e.g., task difficulty). In addition to the within-trial findings, previous UCM studies demonstrated the effects of three constraints on interlimb coordination patterns across multiple trials, as they observed decreased bilateral motor synergies in a specific population (e.g., older adults)[10,12,36] and easier task difficulty (e.g., symmetrical tasks)[9,11]. Similarly, the current findings confirmed the influence of an environmental constraint (i.e., visual information) on bilateral motor synergies consistent with prior results[9,10]. Moreover, the two targeted force levels below 50% of MVC did not alter bilateral motor synergies although the ratio of good and bad variability was affected by the task constraint[13,23]. These findings indicated that the performers showed a tendency to maintain the level of bilateral motor synergies during various submaximal force modulations by interactively modulating the ratios of good variability and bad variability across multiple trials.

The presence of online visual feedback increased bilateral motor synergies implicating more cooperative motor actions between two hands with the reduction of bad variability components across multiple trials. Freitas and colleagues proposed the stability-optimality trade-off phenomenon in human behaviors[37]. Specifically, an optimality strategy represents that the central nervous system selects an optimal motor solution from numerous motor elements (i.e., motor redundancy) by minimizing the variance of force elements produced by two limbs along the UCM line. On the other hand, a stability strategy indicates the organization of numerous motor elements (i.e., motor abundance) for stabilizing task performance by decreasing the variance of force elements along the ORT line resulting in greater index of bilateral motor synergies (i.e., higher good variability relative to bad variability). These two motor control strategies may independently influence actions generating synergetic interlimb movements[28,37-39]. Taken together, our findings suggest that when the simultaneous task-related visual feedback is available, the performer may prefer the stability strategy for successful task performances across multiple trials via increasing bilateral motor synergies while minimizing bad variability components.

As we expected, bimanual force control capabilities within a trial were more improved in the vision condition, as indicated by decreased task error, variability, and regularity. Presumably, providing visual feedback facilitates activation of visuomotor networks contributing to online motor corrections and task stabilization during isometric force control[9,14,25,40]. In addition, the availability of online visual information may positively regulate firing rates on neuromuscular systems by decreasing the neural noise of synaptic input and motor neuron pools[9,41]. Moreover, the performers increased force irregularity in the vision condition indicating more compensatory and adaptive force outputs between hands. A prior study reported increased values of approximate entropy (ApEn) on bimanual forces from no-vision to vision conditions[14]. Given that SampEn analysis may have higher independence of results according to different data lengths[29], we additionally confirmed force regularity reduced by visual information with the advanced nonlinear approach. Perhaps, the presence of visual information decreases environmental entropy while simultaneously increasing motor entropy, referred to as compensatory trade-off effects[42,43].

Importantly, our findings revealed that an increase in bilateral motor synergy across multiple trials from no-vision to vision conditions was positively correlated with the improvements in force control performances (i.e., a reduction of force variability and regularity) collapsed across the three targeted force levels. Ranganathan and Newell reported that the presence of visual information during bimanual finger force control tasks contributed to reducing disturbances on the variability in degrees of freedom (DOFs) at the execution level and facilitating the use of numerous motor solutions at the planning level[7]. Further, the findings suggested that synthesizing motor control processes between execution and planning levels may consequently stabilize task performances[7]. Accordingly, the current findings confirmed the potential relation between bilateral synergetic coordination strategies at the planning level (i.e., between multiple trials) and traditional and temporal structural of motor variability of DOFs produced by two hands at the execution level (i.e., within a single trial).

Moreover, our correlation findings supported a proposition that the motor system may prefer the stability strategy from no-vision to vision conditions because we observed greater bilateral motor synergies with reduced bad variability related to advanced task stabilization patterns such as less variable and regular bimanual force outputs[37]. As revealed in a neuroimaging study, force control improvements in the vision condition were significantly related to visuomotor processing with greater parietal cortical activations[44].

Given that the parietal cortex was highly involved in both motor execution and planning[44-46], the presence of online visual information may increase neural resources for the visuomotor integration contributing to more adaptive and corrective motor strategies at the execution level and updating motor control strategies at the planning level.

Conclusions

The current study revealed that visual feedback during bimanual isometric force control tasks significantly increased bilateral motor synergies across multiple trials while simultaneously reducing bad variability components. An apparent consequence of the improved force control capabilities within a single trial involves reduced force error, variability, and regularity. Importantly, we observed that a higher frequency of bilateral motor synergetic patterns was positively related with more improvements in force control performances from no-vision to vision conditions. These findings suggest that the presence of task-related visual information contributes to improved coordinative behaviors between hands at both planning and execution via potential facilitation of visuomotor cortical activations for task stabilization. Despite the positive effects of task-related visual information on task stabilization across multiple trials and within a trial, how the presence of visual feedback differently influences bimanual force control strategies is still unknown. Thus, future studies should investigate the effects of variations of visual feedback (e.g., visual gain or frequency) on bimanual force control strategies active during motor action planning and execution.

Methods

Participants

Fourteen young adults (mean ± standard deviation age = 21.6 ± 2.3 years; eight females and six males) participated in this study. All participants were right-handed healthy individuals without musculoskeletal deficits in their upper extremities and cognitive dysfunctions. The current study protocols were approved by the University of Florida's Institutional Review Board, and we confirmed that all methods were performed in accordance with the relevant guidelines and regulations. All participants read and signed an informed consent before starting the test.

Experimental setup

We used isometric force control paradigms during bimanual wrists and fingers extension movements consistent with the prior experimental designs[10,13,22]. Initially, the participants sat 78 cm away from a 43.2 cm LED monitor (1024 × 768 pixels; refresh rate = 100 Hz) and placed their forearms on the desk in comfortable positions (i.e., 15–20° of shoulder flexion and 20–40° of elbow flexion). Next, the participants situated their hands and fingers under the customized platforms embedded with two force transducers (MLP-75, Transducer Techniques, 4.16 × 1.27 × 1.90 cm, range = 75 lbs., 0.1% sensitivity). During the tasks, the participants extended their hands and fingers upward against the platforms to produce isometric forces.

Initially, the participants conducted three maximal voluntary contraction (MVC) trials (trial interval = 6 s and rest time between trials = 60 s). Using a mean value of three peak force outputs across the MVC trials, we set three submaximal targeted force levels (i.e., 5%, 25%, and 50% of MVC) for each individual. These targeted force levels have been previously tested and the findings showed that people may produce different force control strategies depending on altered targeted force levels[13,20,23,24].

The goal of each submaximal isometric force control trial was to match and maintain bimanual force production around a targeted force level for 20 s. Based on previous studies[22,25,26], we administered two different visual conditions: (a) vision and (b) no-vision. Specifically, in the vision condition the LED monitor simultaneously displayed the performer's force outputs produced by both hands with a white line trajectory and a targeted force level, a green line centered on the monitor during each 20 s trial. In the no-vision condition, we removed the white force trajectory after the first 5 s, and then the performer saw only a targeted force level for the remaining 15 s. Participants completed 12 trials for each experimental block (i.e., 6 experimental blocks = 2 visual conditions × 3 targeted force levels), for a total 72 submaximal force control trials. During these submaximal force control tasks, we randomly assigned the six experimental blocks to participants with each block set at a constant visual angle (= 1°)[27].

A custom LabVIEW Program (National Instruments, Austin, USA) conducted standardized testing procedures and data collection. All force signals were sampled at the rate of 100 Hz using a 16-bit analog-to-digital converter (A/D; NI cDAQ-9172 + NI 9215 and minimal force unit detection = 0.0016 N) and amplified using a 15LT Grass Technologies Physio-data Amplifier System (Astro-Med Inc.) with an excitation voltage of 10 V and a gain of 200.

Data analyses

For the following offline-data analyses, we initially filtered the raw force data using a bidirectional fourth-order Butterworth filter at 20 Hz of cut off frequency using a custom Matlab program (Math Works™ Inc., Natick, USA). The middle 10 s (i.e., 5–15 s; 1,000 data points) of force signals was most important for minimizing transient effects of early or later motor corrections in a trial.

To estimate bimanual force coordination across trials, we quantified bilateral motor synergies based on the UCM theory[4,6,11,13]. First, we calculated a mean force value for each hand within a trial and normalized the mean force value into fundamental elements pair using a targeted force level. For instance, when a targeted force level is 80 N, a performer may produce 70 N of mean force produced by two hands (i.e., 30 N from left hand and 40 N from right hand). Thus, a pair of normalized fundamental elements included: (a) left hand: (30 N /

80 N) × 100 = 37.5% and (b) right hand: (40 N / 80 N) × 100 = 50%. Finally, this calculation was repeated across 12 trials for each experimental block, and the 12 pairs of normalized fundamental elements were projected to two distinctive lines: (a) UCM line (Fig. 4A) and (b) ORT line (Fig. 4B), respectively.

Insert Figure 4 about here

The variance components projected to the UCM line are associated with successful motor control capabilities (good variability: V_{UCM}). On the other hand, the variance components projected to the ORT line interfere with motor control (bad variability: V_{ORT})[28]. The V_{Index} (i.e., a proportion of V_{UCM} relative to V_{ORT}) indicates an index of bilateral motor synergies ranging from -2 to 2 values (Formula 1). Note that higher values of V_{Index}, close to 2, represent better bimanual coordination patterns across multiple trials[10].

For additional parametric statistical analyses, we performed Z-transformation on all V_{Index} values using Formula 2 consistent with prior findings[11,13].

$$V_{Index} = \frac{V_{UCM}/df_{UCM} - V_{ORT}/df_{ORT}}{V_{TOT}/df_{TOT}}$$

(1)

Where df_{UCM} shows degrees of freedom of V_{UCM} (df = 1), df_{ORT} is degree of freedom of V_{ORT} (df = 1), V_{TOT} indicates the sum of V_{UCM} and V_{ORT}, and df_{TOT} is degrees of freedom of V_{TOT} (df = 2).

$$V_{Index}\ (Z - transformed) = 0.5 \times \ln \frac{2+V_{Index}}{2-V_{Index}}$$

(2)

To assess bimanual force control performance within a trial, we calculated three outcome measures: (a) force accuracy: root mean square error (RMSE), (b) force variability: coefficient of variation (%CV) = SD of force / mean force × 100, and (c) force regularity:

sample entropy (SampEn; Formula 3)[29,30].

$$\mathrm{SampEn}(x, m, r, N) = \ln\left[\frac{C_m(r)}{C_{m+1}(r)}\right] \quad (3)$$

where m is specific pattern length, r is a criterion of similarity in the time series, and $C_m(r)$ indicates occurrence of repetitive patterns of length m in time series x (i.e., force data in the time samples) excluding the self-match [30]. Consistent with a previous study, we used a value of 2 for m and r = 0.2 × standard deviation (SD) of force data[29].

Statistical analyses

All outcome measures (i.e., V_{Index}, V_{UCM}, V_{ORT}, RMSE, CV, and SampEn) were analyzed with two-way repeated measure ANOVAs (Visual Condition × Force Level; 2 × 3). We confirmed the normality of all dependent variables across vision and force level conditions using the Shapiro-Wilk's W test [31] and Levene's test[32]. When the sphericity assumption was violated, we reported the degrees of freedom adjustments using Greenhouse-Geisser[33]. For conducting post hoc analysis, we used Bonferroni's pairwise comparisons. Finally, Pearson's correlation analysis was used to identify potential relationships between changes in bilateral motor synergy and changes in force control performances including force accuracy, variability, and regularity from no-vison to vision conditions. All statistical analyses were performed using the IBM SPSS Statistics 22 (SPSS Inc., Chicago, IL, USA) and we set an alpha level at 0.05.

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Author contributions

HJL, JHL, NK, and JHC contributed to data collection, statistical analyses, data interpretation, and manuscript drafts. NK conceived and designed the study and conducted statistical analyses. All authors approved the final manuscripts.

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Competing interests

The authors declare no competing interests.

Data availability

All data generated or analysed during this study are included in this published article.

Figure Captions

Figure 1. Bimanual coordination across multiple trials using UCM approach (*M*±*SE*). (A) bilateral motor synergy (V_{Index}) for visual conditions (vision versus no-vision) collapsed across the targeted force levels. (B) Good variability (V_{UCM}) for the targeted force levels (5%, 25%, and 50% of MVC) collapsed across the visual conditions. (C) Bad variability (V_{ORT}) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC).

Figure 2. Bimanual force control performance within a trial (*M*±*SE*). (A) Force accuracy (RMSE) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC). (B) Force variability (CV) for the visual conditions (vision versus no-vision) collapsed across the targeted force levels. (C) Force regularity (SampEn) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC).

Figure 3. Correlation findings between changes in bilateral motor synergies and bimanual force control performances from no-vision to vision conditions. (A) negative correlation between bilateral motor synergy (V_{Index}) and force variability (CV) and (B) positive correlation between bilateral motor synergy (V_{Index}) and force irregularity (SampEn).

Figure 4. UCM analysis quantifying variances of fundemental elements projected to the UCM and ORT lines. (A) The 12 pairs of nomalized fundamental elements extracted from each trial (i.e., black circles) projected to both UCM line (i.e., blue line) and ORT line (i.e., dotted red line) at 25% of MVC condition in the vision condition and (B) no-vision condition.

Figures

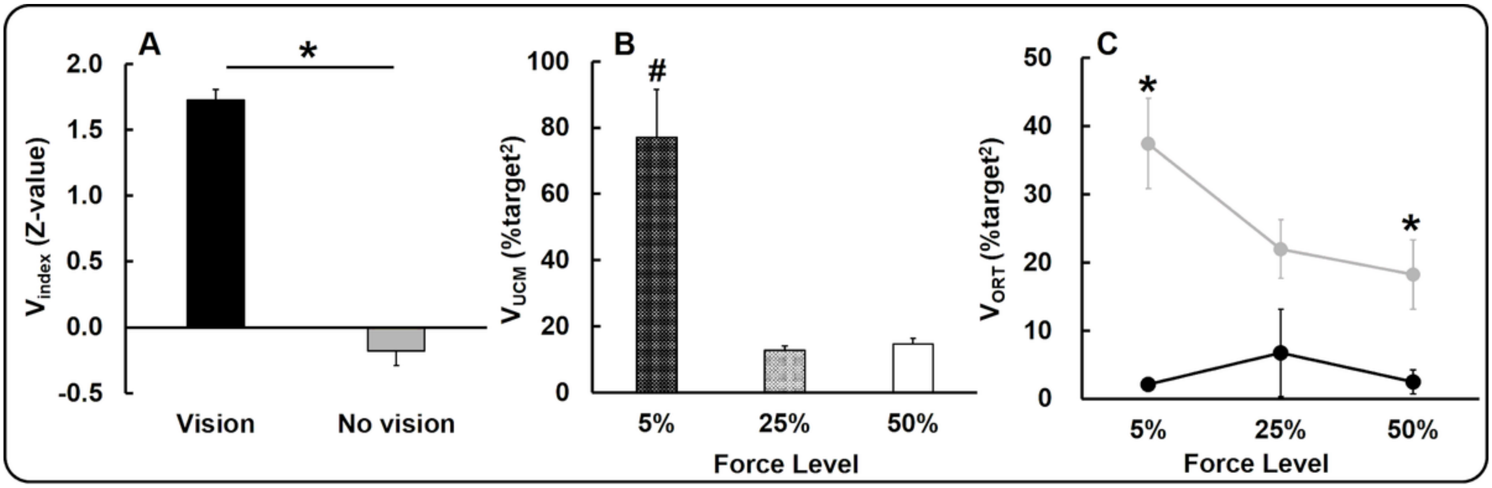


Figure 1

Bimanual coordination across multiple trials using UCM approach (M±SE). (A) bilateral motor synergy (VIndex) for visual conditions (vision versus no-vision) collapsed across the targeted force levels. (B) Good variability (VUCM) for the targeted force levels (5%, 25%, and 50% of MVC) collapsed across the visual conditions. (C) Bad variability (VORT) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC).

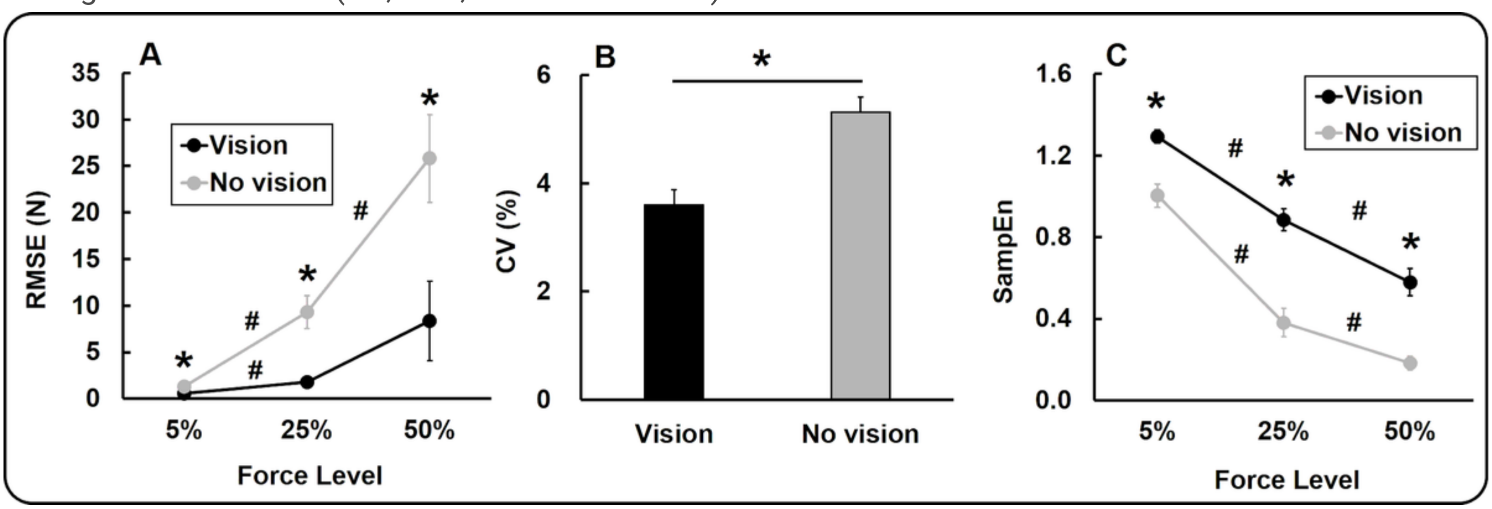


Figure 2

Bimanual force control performance within a trial (M±SE). (A) Force accuracy (RMSE) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC). (B) Force variability (CV) for the visual conditions (vision versus no-vision) collapsed across the targeted force levels. (C) Force regularity (SampEn) for visual conditions (vision versus no-vision) as a function of targeted force levels (5%, 25%, and 50% of MVC).

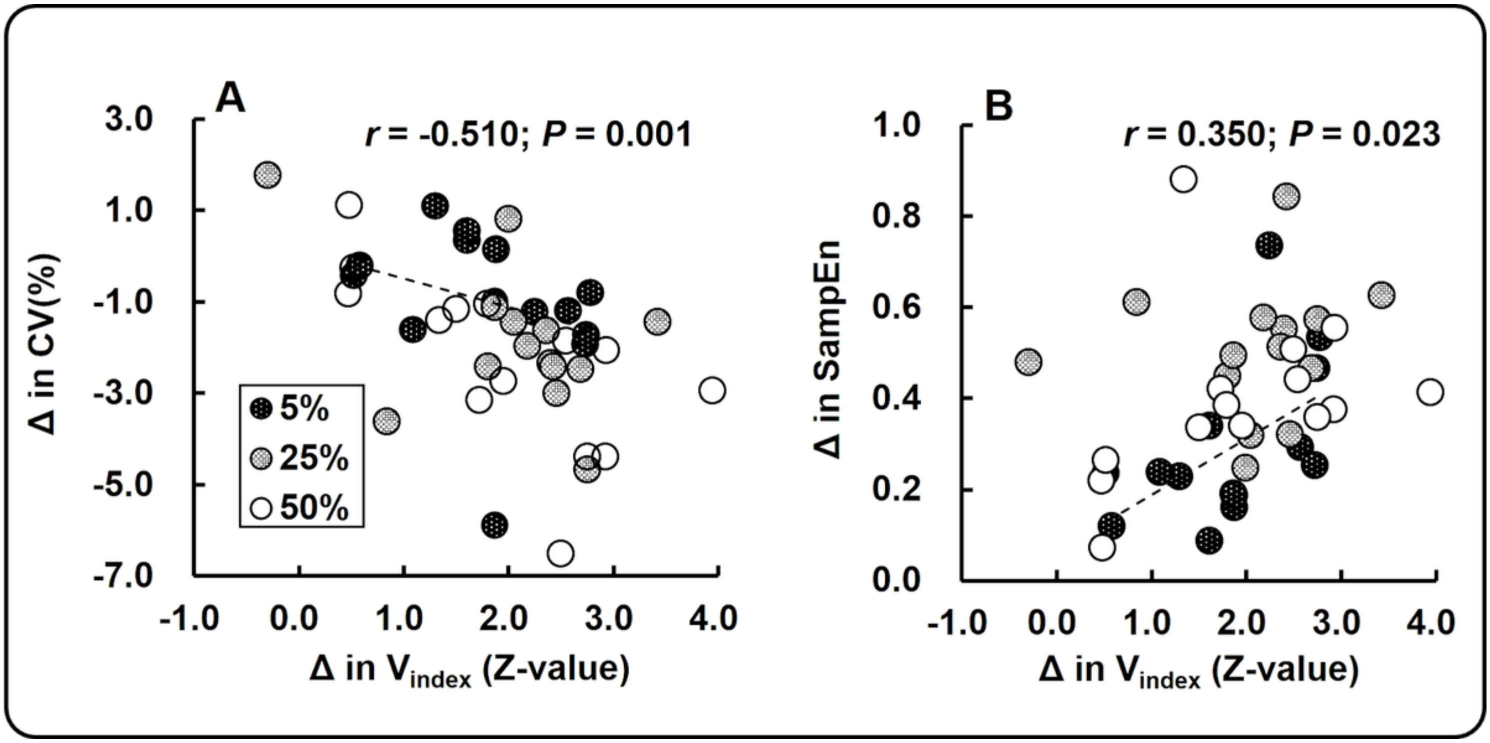
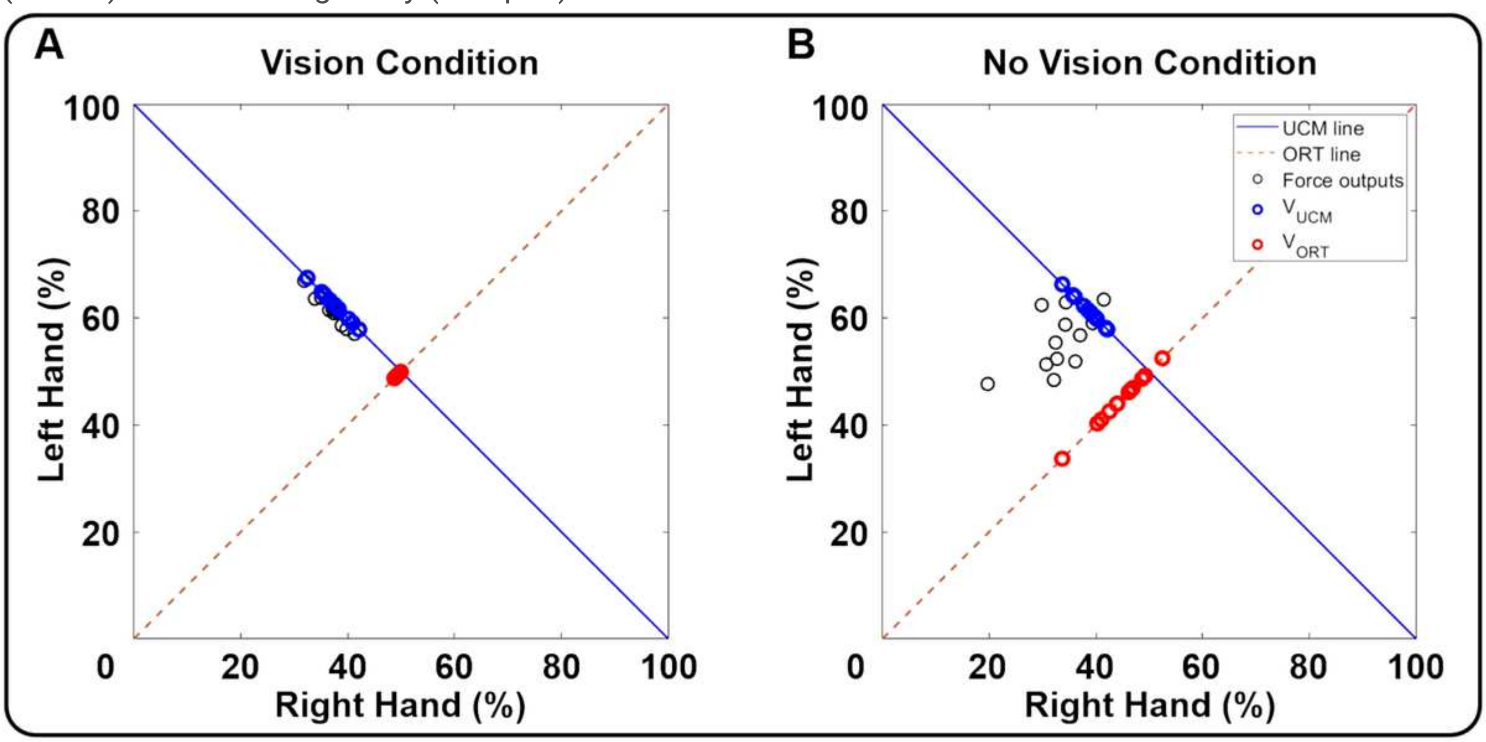


Figure 3

Correlation findings between changes in bilateral motor synergies and bimanual force control performances from no-vision to vision conditions. (A) negative correlation between bilateral motor synergy (VIndex) and force variability (CV) and (B) positive correlation between bilateral motor synergy (VIndex) and force irregularity (SampEn).



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