**Title page**

**Title:** Neural motor control differs between bimanual common-goal vs. bimanual dual-goal tasks

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**Abstract**

Coordinating bimanual movements is essential for everyday activities. Two common types of bimanual tasks are common goal, where two arms share a united goal, and dual-goal, which involves independent goals for each arm. Here we examine how the neural control mechanisms differ between these two types of bimanual tasks. Ten non-disabled individuals performed isometric force tasks of the elbow at 10% of their maximal voluntary force in both bimanual common- and dual-goal as well as unimanual conditions. Using transcranial magnetic stimulation, we concurrently examined the intracortical inhibitory modulation (short-interval intracortical inhibition, SICI) as well as the interlimb coordination strategies utilized between common- vs. dual-goal tasks. Results showed a reduction of SICI in both hemispheres during dual-goal compared to common-goal (dominant hemisphere: *P*=0.04, non-dominant hemisphere: *P*=0.03) and unimanual tasks (dominant hemisphere: *P*=0.001, non-dominant hemisphere: *P*=0.001). For the common-goal task, a reduction of SICI was only seen in the dominant hemisphere compared to unimanual tasks (*P*=0.03). Behaviorally, two interlimb coordination patterns were identified. For the common-goal task, both arms were organized into a cooperative “give and take” movement pattern. Control of the non-dominant arm affected stabilization of bimanual force (*R*2=0.74, *P*=0.001). In contrast, for the dual-goal task, both arms were coupled together in a positive fashion and neither arm affected stabilization of bimanual force (*R*2=0.31, *P*=0.1). The finding that intracortical inhibition and interlimb coordination patterns were different based on the goal-conceptualization of bimanual tasks has implications for future research.

**Keywords:** Bimanual coordination, Task Goal, Short-interval intracortical inhibition (SICI), Interlimb force coordination, motor control

**Introduction**

The majority of our daily activities involve use of two arms (Bailey et al. 2015). Tasks such as dressing and grooming all require one arm to work simultaneously with the other arm in order to complete the tasks. However, depending on the goal of a bimanual task, each arm may have different roles in coordinating the interlimb actions. For example, one type of bimanual tasks is where two arms are required to achieve a single and united functional goal (common-goal) either with similar movements from each arm, such as holding a food tray or pulling out a drawer, or with complementary movements from each arm, such as holding a bottle of water with one arm and opening the cap with the other arm. Regardless of differences of movements involved in the arms, during this type of bimanual task, both arms share a single focus, and they are temporally and spatially constrained to a specific common-goal. The two arms have to coordinate with each other with respect to the timing and sequences of movements in order to accomplish these task (Kazennikov et al. 2002; Diedrichsen 2007; Diedrichsen and Dowling 2009) and the success of this type of bimanual task is highly dependent on the cooperation between the two arms. In contrast, other types of bimanual tasks involve independent goals (dual-goal) for each arm either with similar movements, such as holding a glass of water with one arm and a bottle with the other arm, or with distinct movements, such as using a computer mouse with one arm and typing with the other arm. During this type of bimanual tasks, each arm is assigned with an independent goal, and the successful performance of one arm is not necessarily affected by the performance of the other arm.

Most research to date has focused on bimanual dual-goal tasks to understand how one arm influences the other while pursues independent goals. It is well-known that there is a “interlimb coupling” effect prevailing during bimanual dual-goal tasks (Kelso et al. 1979; Kelso 1984; Swinnen 2002). Studies have demonstrated that both arms tend to produce similar forces (Heuer et al. 2002; Diedrichsen et al. 2003), directions (Swinnen et al. 2001), and frequencies (Peper et al. 1995) even when disparate movements were required for each arm. These coupling effects were not only demonstrated in behavioral movements, but also reflected in cortical control mechanisms (Cattaert et al. 1999; Cardoso de Oliveira 2002). For example, one study has found an enhancement of cortical excitability and decrement of short-interval intracortical inhibition (SICI) of the primary motor cortex of the moving arm during active-passive bimanual mirror movement tasks (Stinear and Byblow 2004). Moreover, study participants with greater interhemispheric inhibition (IHI) capacity demonstrated poorer motor performance during bimanual independent tasks with separate goals compared to those with less IHI capacity (Fling and Seidler 2012). These results suggest that cortical inhibitory modulatory circuits, either within or between hemispheres, may be involved in coordination of bimanual actions, and provide insights about the underlying neural control mechanism related to dual-goal tasks.

Nevertheless, in real life, most of our daily activities require two arms to cooperate with each other to accomplish a shared common-goal. It remains uncertain whether the experimental findings of neural control mechanisms, for example, the intracortical inhibitory modulation from dual-goal tasks could transfer to those of common-goal tasks. Previous studies have primarily focused on movement control of two arms when they are constrained by a common-goal using kinematic or kinetic analysis. Moreover, a variety of common-goal tasks including symmetrical and asymmetrical movement tasks or different movement speed ratio of the two arms were examined in those previous studies (Diedrichsen 2007; Diedrichsen and Dowling 2009; Duque et al. 2010; Sainburg et al. 2013; Kantak et al. 2016). These studies have characterized the movement profiles of the two arms when they share a single goal. However, the basis of neural mechanisms, particularly the intracortical inhibitory circuit associated with control of common-goal tasks, has largely been unexplored, even for simple movements. To address this issue, we examined the levels of intracortical inhibition involving common-vs. dual-goal tasks and compared them to those of unimanual tasks using movements that were simple and identical for both arms.

The purpose of this study was to investigate the neuro-motor control of bimanual actions constrained by a common goal compared to bimanual actions that were driven by independent goals (dual-goal) and also unimanual goals. In particular, we examined the intracortical inhibitory modulation (short-latency intracortical inhibition, SICI) involved in these two bimanual tasks and compared them to unimanual tasks. Participants performed bimanual isometric force contraction tasks by flexing their elbows to match to a single target line (common-goal) or two separate lines (dual-goal). This simulates gross-motor bimanual daily activities, such as, holding up a food tray using both arms (common-goal) or lifting water bottles with each arm (dual-goal). We also assessed task performance with a focus on force coordination and force variability in bimanual conditions. Based on previous literature, we hypothesized that SICI would decrease in both common-and dual-goal tasks compared to unimanual tasks. Furthermore, there would be greater reduction of SICI in both hemispheres in common-rather than dual-goal tasks when compared to unimanual tasks. In addition, stronger interlimb force coordination and less force variability would be seen in bimanual force during common-versus dual-goal tasks suggesting that the two arms were organized into a functional unit when sharing a united focus.

**Materials and Methods**

Participants

A convenience sample of ten non-disabled individuals (mean age: 30.82±5.84 years; 5 female) was recruited from the local universities. They were graduate students and/or research assistants working in the local universities but were not informed of the hypotheses or purpose behind the study. All participants were right handed as indicated by the Edinburgh Handedness Inventory (EDH) Scale (mean EDH scores: 88.62 ±12.02%) (Oldfield 1971). None of the participants had any medical or psychiatric history, nor any contraindications to TMS (Wassermann 1998; Rossi et al. 2009). All participants signed informed consent and all study procedures were approved by the Institutional Review Board (IRB) of School of Medicine at the University of Maryland Baltimore, and followed the 1964 Helsinki Declaration and its later amendments.

Experimental Tasks

Participants were seated in a cushioned reclining chair with elbows positioned at 90° flexion and forearms in neutral position, and stabilized in arm cuffs. They performed isometric elbow flexion tasks in three conditions: (1) unimanual condition using the right or left arm independently to match to a single target line, (2) bimanual condition with independent goals for each arm (dual-goal, two distinct target lines corresponding to the right and left arm), and (3) bimanual condition with a common-goal for both arms (a single target line corresponding to the total force of both arms). Prior to testing, participants performed a maximal voluntary contraction (MVC) in each of these three tasks. Ten percent of the MVC for each condition was set as the target level to match for testing based on evidence of SICI in the previous study and to minimize fatigue during tests (Ortu et al. 2008). Participants were instructed to isometrically flex their elbows to match the target level as closely as they could and hold this continuously for at least 10 seconds with an inter-stimulus interval≧10 seconds to minimize fatigue during TMS data collection. Rest break was also provided in between if needed. A computer monitor was placed 1 meter away from participants to provide real-time visual feedback of the force with respect to each condition.

Paired-pulse Transcranial Magnetic Stimulation (pp-TMS) paradigm for short-interval intracortical inhibition (SICI)

TMS pulses were applied using two Magstim 200 stimulators through a single figure-of-eight coil (70 mm diameter of each wing) attached to a BiStim module (Magstim Company, Dyfed, UK). The coil was held tangentially to the scalp with the handle pointing backward and laterally at an angle of 45 degrees in the sagittal plane. Motor evoked potentials (MEPs) were recorded from biceps brachii muscles of both arms. Two bipolar Ag-AgCL surface electrodes were placed on the belly of each biceps brachii muscle and muscle activities were recorded by a wireless EMG system (TeleMyo Direct Transmission System (DTS), Noraxon, USA, Inc.). EMG signals were sampled at 1000 Hz with a low-pass filter at 450 Hz. The optimal site for stimulation (hotspot) and the active motor threshold (AMT) were determined according to guidelines in the literature (Rothwell et al. 1999; Rossini et al. 2015). The active motor threshold (AMT) was defined as the lowest intensity producing MEP amplitudes exceeding 200 μV in > 5 of 10 consecutive stimulations while subjects performed isometric elbow flexion tasks at 10% MVC.

A paired-pulse TMS paradigm was used to examine short-interval intracortical inhibition (SICI) of both dominant and non-dominant hemispheres during three conditions. In this paradigm a sub-threshold conditioning stimulus (CS) was followed by a supra-threshold test–stimulus (TS) at different inter-stimulus intervals (ISI) (Kujirai et al. 1993). The resulting paired-pulse conditioned MEPs were compared to the single-pulse non-conditioned test MEPs and expressed as a MEP ratio. SICI should decrease with increasing MEP ratio.

The ideal intensity for assessing SICI has not been determined in bimanual conditions with active contraction. Consistent with protocols adopted in the literature, we performed pilot tests using CS intensity ranged from 50-80% AMT and TS intensity of 120% AMT at ISI of 2 ms (Ilic et al. 2002). We found that 50% AMT demonstrated the greatest inhibition during bimanual isometric elbow flexion conditions (Davey et al. 1994; Awiszus et al. 1999; Fisher et al. 2002). Thus, the CS was applied at 50% AMT and the TS was applied at 120% AMT with ISI at 2 ms.

To allow for equal comparison between unimanual and bimanual conditions, the intensity of single pulse TMS (TS intensity) in bimanual conditions was individually adjusted until the averaged single-pulse test MEP was within one standard deviation of the averaged single-pulse test MEP obtained in the unimanual condition. Thus, the testing orders of experimental conditions were unimanual conditions first followed by dual-goal and then common-goal conditions. A total of 20 TMS pulses, 10 single-pulse followed by 10 paired-pulse was delivered in each condition for both dominant and non-dominant hemispheres. MEP data was analyzed offline using a customized MATLAB program (Math WorksTM Inc., Natick, USA).

Force measurement

The force produced by each arm was recorded by two force transducers (Transducer Techniques, CA) mounted under the armrests. The force signal was sampled at 1000 Hz and filtered by a zero-phase low pass filter with a cutoff frequency of 10 Hz. Data acquisition was controlled using a customized MATLAB program (Math WorksTM Inc., Natick, USA). The force signal from 2 seconds to 750 milliseconds before a TMS pulse was visually inspected to ensure no TMS artifact effects and was used for analysis of force outcomes (interlimb force correlation and force variability). A total of 10 trials were collected for each subject under each experimental condition. Pearson’s correlation was used to assess the correlation of force signal between the arms during bimanual common-and dual-goal tasks. A positive Pearson’s correlation coefficient would suggest that two arms move in the same direction; whereas a negative correlation would indicate that two arms coordinate but move in the opposite directions.

Outcome variables

The outcomes of this study were short-interval intracortical inhibition (SICI) involving three experimental conditions and force variables including interlimb force correlation and force variability in bimanual common-and dual-goal tasks. SICI was expressed as a percentage of the paired-pulse conditioned MEPs relative to the averaged single-pulse test MEPs for each condition (MEP ratios). For the force measurement, we included two major outcome variables, interlimb force correlation and force variability, to describe motor control patterns between the arms. Interlimb force correlation refers to the coordination of force between two arms during dual-and common-goal tasks. Force variability refers to the ability to control and stabilize force under the constraint of the task. Force variability was calculated using the coefficient of variation (CV) around the mean and reported as a percent (%). We assessed force variability of each arm (CVDom= CV of the dominant arm and CVNon-dom= CV of the non-dominant arm) as well as force variability of both arms (bimanual force variability, CVSum= the CV of total force produced by both arms) during bimanual conditions to determine whether the task goal (dual-goal vs. common-goal) would affect the motor control strategies of the arms.

**Statistical Analysis**

The Shapiro-Wilk test was used to examine the distribution of the data. Repeated Measures ANOVA were used to compare MEP ratios (SICI) within subjects between three conditions. The Mauchly's test was implemented to assess the assumption of sphericity. If the assumption of sphericity was violated, we used the Greenhouse-Geisser method to correct the violation. The Bonferroni correction procedure was used for post-hoc multiple comparisons analysis. The same repeated measures ANOVA procedures were also used to compare the intensity of TS and CS between three conditions.

For the force data, trials with positive correlation or trials with negative correlation were grouped together and analyzed separately for each subject and were used to determine the strength of interlimb coupling in the same direction (positive correlation) or opposite direction (negative correlation) during the common-and dual-goal tasks. The McNemar Chi-square Test was used to compare the changes in the proportions of negative correlation coefficient trials between the common-and dual-goal tasks (Hoffman 1976; Eliasziw and Donner 1991). The Pearson’s correlation coefficient of all force trials was converted into normally distributed data using the Fisher r-to z transformation, averaged within each subject and compared between common-and dual-goal conditions using the paired t-test (Fisher 1915; Silver and Dunlap 1987).

The paired t-test was used to compare force variability of each arm (CVDom and CVNon-dom) and both arms (CVSum) between common-and dual-goal conditions. We also performed a linear regression analysis to compare the force variability contributed by each arm to the force variability produced by both arms in bimanual tasks. The explanatory variable was interlimb force variability (CVNon-dom minus CVDom). The dependent variable was bimanual force variability (the variability of total force produced by both arms, CVSum) (Kang and Cauraugh 2014). A positive relationship between the explanatory and dependent variables would suggest that greater force variability produced by the non-dominant than dominant arm was associated with increased bimanual force variability and vice versa for a negative relationship. A significant relationship would also indicate that interlimb force control was associated with bimanual force stabilization. *R*2 measured the goodness-of-fit for this model. For all statistical tests, alpha level was set as 0.05.

**Results**

Short-interval intracortical inhibition (SICI)

Figure 1 illustrates an example of the paired-pulse MEP in one subject in the bimanual common-goal, dual-goal and unimanual conditions. For the dominant hemisphere, SICI was obtained from all participants (N=10). For the non-dominant hemisphere, SICI was collected from seven participants due to the higher motor threshold presented in the other three individuals. The averaged AMT was 60.8±12.24% for the dominant hemisphere (range:32-78%) and 56.5±11.9% for the non-dominant hemisphere (range: 32-74%). The intensities of TS and CS were comparable between unimanual, common-and dual-goal conditions for the dominant (TS: *F*(2,18)=0.89, *P*=0.43; CS: *F*(2,18)=0.73, *P*=0.49) as well as the non-dominant hemisphere (TS: *F*(2,12)=2.59, *P*=0.12; CS: *F*(2,12)=3, *P*=0.09).

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Insert Figure 1 about here

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Figure 2 shows the mean MEP ratio of the dominant hemisphere in bimanual common-goal, dual-goal and unimanual tasks. Significant main effects were found between three conditions (*F*(2,18)=19.39; *P*<0.001). There was significantly reduced intracortical inhibition (SICI) in the common-goal (M=86.8±3.6% of baseline MEP) compared to the unimanual tasks (M=73.4±3.8% of baseline MEP) (*P*=0.03), as well as, the dual-goal (M=98.12±1% of baseline MEP) compared to the unimanual tasks (*P*=0.001). Furthermore, significantly reduced SICI was also found in the dual-goal compared to the common-goal tasks (*P*=0.04).

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Insert Figure 2 about here

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Figure 3 shows the mean MEP ratio of the non-dominant hemisphere in the bimanual common-goal, dual-goal and unimanual tasks. Significant main effects were found between the three conditions (*F*(2,12)=16.54, *P*<0.001). There was significantly reduced SICI in the dual-goal (M=98.46±1.14% of baseline MEP) compared to unimanual tasks (M=84.91±1.87% of baseline MEP) (*P*=0.001). In addition, significantly reduced SICI was also found in the dual-goal compared to the common-goal (M=89.95±1.74% of baseline MEP) tasks (*P*=0.03). However, no differences were found between MEP ratios of the common-goal and unimanual tasks (*P*=0.41) even though the mean MEP ratio was greater in the common-goal compared to the unimanual tasks.

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Insert Figure 3 about here

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Bimanual force coordination.

*Interlimb force correlation.* Two patterns of interlimb correlation (positive and negative) were identified in both common-and dual-goal tasks (Figure 4). There were no significant differences in the strength of interlimb coupling between the common-and dual-goal conditions based on the positive correlation trials (*t*(9)=1.68, *P*=0.13). The strength of interlimb positive correlation was moderate and comparable between the two conditions (common-goal=0.54±0.12; dual-goal=0.59±0.13). On the other hand, for the negative correlation trials, the strength of interlimb coupling was significantly higher in the common-goal compared to dual-goal tasks (*t*(9)=3.78, *P*=0.01; common-goal= –0.4±0.27, dual-goal= –0.13±0.14). Furthermore, significantly greater proportions of negative interlimb correlation trials were found in the common-than dual-goal tasks indicating that a different interlimb coordination strategy was adopted in the common-goal condition (*P*=0.01).

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Insert Figure 4 about here

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*Force variability.* Figure 5 illustrates the coefficient of variation (CV) of force from each arm and from both arms in the common-and dual-goal tasks. The force variability of both arms (CVSum) was significantly reduced in the common-goal (M=2.4±0.91%) compared to the dual-goal tasks (M=3.29±1.37 %) (*t*(9)=2.57, *P*=0.03) suggesting that bimanual performance was more stable in the common-rather than the dual-goal tasks. In addition, significant differences were also seen in the non-dominant arm between the two bimanual conditions (*t*(9)= –2.74, *P*=0.02). There was higher force variability in the non-dominant arm (CVNon-dom) during the common-goal (M=5.48±2.65%) than the dual-goal (M=3.49±1.18%) tasks. Although not reaching statistical differences (*P*=0.14), the force variability of the dominant arm was also higher in the common-goal (M=6.1±2.57 %) compared to the dual-goal (M=4.23±2.14%) tasks.

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Insert Figure 5 about here

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*Interlimb interaction.* Based on the linear regression model, we found a significant and positive relationship between interlimb force variability (CVNon-dom – CVDom) and bimanual force variability (CVSum) in the common-goal task (*F*(1,8)=22.29, *R2*=0.74, *P*=0.001) (Figure 6). Greater force variability of the non-dominant than the dominant arm was associated with increased bimanual force variability in the common-goal task. This result showed that the stabilization of bimanual performance was affected more by the control of the non-dominant than the dominant arm. However, we did not find this relationship in the dual-goal tasks (*F*(1,8) =3.48, *R2*=0.31, *P*=0.1) (Figure 7).

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Insert Figure 6 & 7 about here

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**Discussion**

In the present study, we examined neuro-motor control of bimanual actions constrained by a common goal compared to bimanual actions that were driven by independent goals (dual-goal), and also unimanual goals. We found reduced SICI in both hemispheres in the dual-goal compared to common-goal, as well as, unimanual tasks. In contrast, while we also saw reduced SICI during the common goal task, it was only seen in the dominant hemisphere when compared to the unimanual task. The two arms were well-coordinated with each other in both bimanual tasks, but they exhibited different coordination patterns based on task goals. During the common goal task, we found a larger proportion of negative correlation trials and a stronger negative correlation between the arms indicating more of a “give and take” of forces during this type of task. This resulted in reduced variability in overall bimanual force but greater force variability in each arm, particularly in the non-dominant arm. We also found that the greater force variability of the non-dominant than the dominant arm was associated with increments of bimanual force variability during the common-goal task, which emphasizes the relevance of controlling the non-dominant arm when both arms were constrained by a united-goal, but not dual-goal task.

To the best of our knowledge, this is the first study comparing the modulation of intra-cortical inhibitory circuits (SICI) of bimanual tasks with a common-goal vs. dual-goals. Consistent with our hypothesis, a reduction of SICI was found in the both bimanual tasks when compared to the unimanual task. With regard to the dual-goal task, cortical disinhibition was shown in both dominant and non-dominant hemispheres. This is in contrast to the study by Stinear and Byblow (2004) who showed a reduction of SICI in the non-dominant hemisphere only when compared to unimanual tasks. In their study, subjects performed bimanual symmetrical wrist flexion-extension movements in a passive-active mode, with one arm actively moved simultaneously with the other arm that was driven passively by a controller. In our study, the two arms are required to move actively and symmetrically together in pursuit of independent goals. This active and symmetrical patterns of the two arms may potentially enhance bilateral coupling between the arms, which in turn leads to disinhibition of both dominant and non-dominant hemispheres during the dual-goal task (Diedrichsen et al. 2003; Carson 2005; Grefkes et al. 2008).

Counter to our hypothesis, the decrease of SICI we observed was shown in the dominant but not the non-dominant hemisphere during the common-goal tasks. This result suggests that the dominant primary motor cortex (M1) may play a more critical role than the non-dominant M1 in coordinating two arms when they are united by a common goal. Indeed, several previous studies have shown that the dominant hemisphere, including M1 and other secondary motor areas, produced greater influence on the homologous regions of the non-dominant hemisphere than vice versa during bimanual movement tasks (Serrien et al. 2003; Maki et al. 2008; Walsh et al. 2008). In a fMRI study by Aramaki et al. (2006), they further found a suppression of activations of the non-dominant M1 during bimanual mirror movement tasks which suggested that movements of the non-dominant arm could be partly modulated through uncrossed ipsilateral corticospinal pathways from the dominant hemisphere. The motor dominance phenomenon has been demonstrated not only in the control of contralateral arm but also in the modulation of ipsilateral arm (Ziemann and Hallett 2001; Vines et al. 2008). It is possible that inhibitory control mechanisms from the motor dominant M1 have the capacity to coordinate the two arms through contralateral, and at least partially through ipsilateral motor pathways during a bimanual task where both arms are united by a common-goal.

Another novel finding of this study is that the levels of intracortical disinhibition were different between the common-vs. dual-goal tasks. We found a greater disinhibition of both hemispheres during the dual-than common-goal tasks suggesting that there may be a mutual activation of both hemispheres during the dual-goal tasks. This result may indicate that both hemispheres can exhibit similar levels of control over each arm when independent goals are the same, and there may be less influence of hemispheric dominance during the dual-compared to common-goal tasks. In line with our findings, some studies have not found hemispheric differences in cortical activation during bimanual tasks with independent goals (Fox et al. 1985; Toyokura et al. 1999). One study also showed that TMS disruption of the right and left hemispheres caused almost equal interference effects in bimanual independent and rhythmic in-phase tasks (Chen et al. 2005). However, the hemispheric dominance during bimanual tasks has shown equivocal results in behavioral and neural studies. Some studies have demonstrated left hemisphere supremacy and influence of the dominant to non-dominant arm (Stucchi and Viviani 1993; Swinnen et al. 1996; Viviani et al. 1998; Serrien et al. 2003) while the others found no evidence of hemispheric dominance (Foltys et al. 2001; Chen et al. 2005). These heterogeneous findings may be due to the differences in the tests and tasks adopted in those previous studies. One major strength of our study is that identical movements were required for both bimanual dual-and common-goal conditions with the differences residing in the type of goal only. In our study, there was a hemispheric difference of SICI modulation during the common-goal, but not dual-goal tasks. This could be due to the high demands of coordination between the arms when they are constrained by a common goal. During the common-goal task, the two arms are required to be temporally and spatially coordinated with each other in order to achieve the united goal, which makes it a more complex task compared to the dual-goal task even though the movements required were the same. Indeed, previous studies have reported a high involvement of the left hemisphere during complicated visuomotor tasks (Haaland et al. 2004; Serrien and Spapé 2009). The greater requirement of visuomotor and interlimb coordination during the common-goal condition could be the reason why the hemispheric dominance was observed in the common-rather than dual-goal task. However, it should be noted that the hemispheric dominance is a complex phenomenon in that brain dominance may depend on various characteristics of the tasks including the task goal.

In addition to SICI, the neural circuits of interhemispheric interaction, which include the dual-pulse measurement of interhemispheric inhibition (IHI) or ipsilateral silent period (ISP), have also been reported to be involved in modulating bimanual tasks. Perez et al. (2014) investigated the levels of transcallosal inhibition in the biceps and triceps during bimanual isometric elbow flexion or extension tasks in dual-goal conditions. They found that the ISP was greater during the contraction of the homologous muscles (flexion-flexion and extension-extension) than that of the non-homologous muscle pairs, suggesting that there was an increased interhemispheric inhibition when both arms completed two separate goals. Other studies have also demonstrated task-dependent effects of IHI on the hand muscles in bimanual dual-goal tasks, with greater IHI showing in the symmetrical than asymmetrical conditions (Tazoe et al. 2013). Specifically, individuals with greater IHI had poorer performance when required to perform different movements with each arm (Fling and Seidler 2012). Similarly, in our study, participants performed bimanual tasks with both arms moving either symmetrically with two separate goals or symmetrically with a common goal.

Based on the findings of the above studies, it is possible that the IHI was elevated during our dual-goal conditions in order to reduce the extra motor overflow between hemispheres, such that each arm could move symmetrically matching the respective target force level without interference (Cunningham et al. 2017). This increased IHI may reduce the levels of SICI, and accompanied by the local activation of each hemisphere during voluntary contraction, it may lead to a greater reduction of SICI in both hemispheres in the dual-compared to the common-goal tasks (Daskalakis et al. 2002). In contrast, during the common-goal tasks, the two arms are required to be tightly coordinated with each other under the constraint of a united goal. The motor overflow between hemispheres could serve as an adaptive strategy to promote flexibility and communication between the arms (Cunningham et al. 2017), which in turn may lead to a decrement of IHI and cause higher SICI in the common-compared to dual-goal conditions (Daskalakis et al. 2002). Although we did not directly measure IHI in this study, it is likely that the SICI could also be affected by interhemispheric interaction with respect to the goals of bimanual tasks. Further investigation is needed to reveal the relationship of IHI and SICI in the bimanual dual-and common-goal tasks.

Behaviorally, we found two different interlimb coordination patterns whose differences were characterized by interlimb force correlation and force variability of the arms. As expected, we found a positive correlation of force between the arms during both bimanual common-and dual-goal tasks. This positive interlimb correlation indicates that the arms were coupled together, and exerted forces simultaneously in the same direction to match to targets (Kennedy et al. 2016). We further identified another coordination strategy, characterized by negative interlimb correlation between the arms in dual-and common-goal conditions. This coordination strategy was stronger and predominantly emerged during the common-goal task. This negative interlimb correlation represents an alternative motor control strategy in which the two arms coordinated with each other, but in a cooperative “give and take” fashion. The force of one arm increased while the force of the other arm decreased as long as the final goal, which is the total motor output required for both arms, was maintained for a bimanual common-goal task. On the contrary, we did not found this negative interlimb synergy prevailing in the dual-goal task where two arms were mostly coupled with each other in a positive manner when matching to independent goals.

As expected, we found a reduced variability of overall force from both arms in the common-goal compared to dual-goal tasks. Surprisingly, while the overall force variability was reduced, the variability from the non-dominant arm was actually higher in the common-compared to the dual-goal tasks. Though not reaching statistically differences, the force variability from the dominant arm was also higher in the common-compared to the dual-goal tasks. This finding of reduced overall variability from both arms accompanied by the freedom of variability allowed for each arm was compatible with the concept of a “movement synergy” (Turvey 1990; Gelfand and Latash 1998) and it agrees with the principle of “motor abundance” (Kugler et al. 1980; Latash et al. 2001). The principle of motor abundance states that all degrees of freedoms (DOFs) are required in the control of movements in order to assure the stability as well as the flexibility of the motor performance. The central controller allows high variability of each element if it does not affect the stability of the desired actions (Latash et al. 2007). In our study, for the common-goal task, the flexibility was allowed for each arm, and particularly the non-dominant arm, as long as the overall stability of task performance was maintained for both arms. However, we did not find this particular bilateral synergy generated during the dual-goal task. For the dual-goal task, it is possible that stabilization of force of each arm is also as critical as the stabilization of total force when there are two independent goals for each arm (Tseng and Scholz 2005).

In addition to the direct comparison of force variability between common- and dual-goal conditions, we examined whether the variability differences between the arms would affect the overall bimanual force performance. We found that the greater force variability of the non-dominant than the dominant arm was associated with increments of bimanual force variability in the common-goal, but not dual-goal task. This novel finding suggests that the control of the non-dominant, rather than the dominant arm was critical to bimanual force performance when both arms are constrained by a united goal. Two potential explanations could account for this finding. First, the higher variability of the non-dominant than the dominant arm could reflect a sign of a less efficient control of the non-dominant arm and/or noise coming from the non-dominant arm during the bimanual task (Harris and Wolpert 1998; Cohen and Sternad 2009; Tseng et al. 2009; Shmuelof et al. 2012). This lack of control of the non-dominant arm caused a de-stabilization of the bimanual force performance, and therefore resulted in the increment of variability in the overall force performance of two arms. This would indicate that to switch to a more unimanually controlled strategy using the dominant arm to compensate for the less efficiently controlled non-dominant arm may assist in stabilization of bimanual force performance during a common-goal task. On the other hand, one could argue that a more beneficial approach would be to train the control of the non-dominant arm in order to improve bimanual performance in a common-goal task.

The second potential explanation is that the non-dominant arm could function as the primary adjusting arm when both arms are constrained by a united goal. Given the nature of the adjusting arm, the variability of the non-dominant arm would be higher and correlated with the overall bimanual force variability. Previous studies have shown that there are distinct neural control strategies responsible for the dominant and non-dominant arm during unimanual tasks (Sainburg and Kalakanis 2000; Haaland et al. 2004). Specifically, the non-dominant hemisphere has been shown to be specialized in controlling the accuracy of the final position of the arms, again during unimanual movements (Sainburg 2002; Shabbott and Sainburg 2008). Our study extends previous findings and further demonstrates that the non-dominant arm may also be capable of controlling and modulating the accuracy of overall bimanual movement performance in order to match to a common-goal as precisely as possible. Regardless of which explanations is true, both indicate the relevance of controlling the non-dominant arm during a bimanual common-goal task. On the contrary, there was no such relationship found in the dual-goal task. This suggests that the stability of bimanual force performance is not affected predominantly by one arm over the other when each arm has its individual goal, and supports a conclusion that different coordination strategies were indeed adopted between the common- and dual-goal conditions.

The findings from our study may have clinical implications for arm rehabilitation post-stroke. First, our observation of differences in neuro-motor control between the common- and dual-goal task indicates that not all bimanual tasks are the same, and that specific arm training paradigms should be designed according to the constraints of bimanual tasks. Current bilateral arm training approaches are mostly focused on practice of bilateral actions involving independent goals (Whitall et al. 2000; Stewart et al. 2006; Van Delden et al. 2012). Our study highlights the importance of extending current bilateral arm training protocols to include more cooperative tasks that have a united goal for both arms. Second, training of the non-dominant arm may be beneficial for improving interlimb coordination in the context of cooperative tasks. For individuals with dominant hemisphere stroke, practice of the non-paretic/non-dominant arm, in addition to the paretic/dominant arm, may be able to assist in recovery of bimanual coordination in a cooperative task.

*Limitations.* There are five limitations should be considered for the present study. First, although our paradigm was well controlled using isometric force contraction of elbow flexors, the findings of our study may not necessarily translate to other types of bimanual common-goal tasks such as complicated functional movement tasks, or even other types of isometric force tasks with different arm postures. Second, we only included right-handed participants. Studies have shown that the hemispheric asymmetry of cortical output, interhemispheric inhibition (Yahagi and Kasai 1999; Bäumer et al. 2007), and hand-control characteristics are different between right-and left handed individuals (Kagerer 2016). Therefore, we cannot generalize the findings of this study to left-handed individuals. Future studies could examine neural control mechanisms of the bimanual common-and dual-goal task in people who are left-hand dominant and using more complex functional tasks. Third, the order of the experimental conditions was fixed to enable equal comparison of the MEP ratio across conditions. Therefore, we cannot rule out the possibility of an order effect, and the findings of this study may not be generalizable to other experimental contexts. Fourth, the sample size is small. Caution should be taken when transferring the findings of this study to a wider group of individuals. A larger experimental trial with a randomized sample of participants would be needed to further confirm findings of this study. Fifth, we did not directly measure interhemispheric inhibition (IHI) although we provided an explanation of how IHI may affect SICI with respect to the task goals. Future studies could examine the role of IHI on SICI in modulating bimanual tasks with different goals. Lastly, it should be noted that our findings might not readily generalize across other task paradigms because of the specific parameters used in this study. Future studies could examine whether our findings of hemispheric differences between common- and dual-goal tasks remain the same using different types of bimanual tasks and different parameters of paired-pulse TMS.

**Conclusions**

Our study demonstrated that neuro-motor control was different between bimanual common-vs. dual-goal tasks even though the movements required were identical and well-constrained. The intracortical inhibitory control of the dominant hemisphere seemed to be crucial for modulating a common-goal task whereas both hemispheres may share similar levels of intracortical inhibitory control during a dual-goal task. Furthermore, these differences were also reflected in interlimb coordination patterns that showed “give and take” vs. “coupling together” and a differential role of the non-dominant arm. These findings provide interesting implications to understand how conceptualization of task goals (common-vs. dual-goal) influence neural control strategies of two arms during bimanual tasks.

**Conflict of Interest:** The authors declare that they have no conflict of interest.

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**Figure captions**

**Fig. 1** Paired-pulse motor evoked potentials (MEPs) recorded from the dominant BB muscle from a representative participant during the bimanual common-goal, bimanual dual-goal and unimanual tasks. The y-axis is showed in volts (V)

**Fig. 2** Mean MEP ratio as the percentage of baseline test MEP in the dominant hemisphere under three conditions. The data is presented as mean ± standard error \**P*<0.05

**Fig. 3** Mean MEP ratio as the percentage of baseline test MEP in the non-dominant hemisphere under three conditions. The data is presented as mean± standard error \**P*<0.05

**Fig. 4** Examples of force profiles in the bimanual common-goal task. **a.** A positive interlimb correlation trial with the correlation coefficient of 0.69. **b.** A negative interlimb correlation trial with the correlation coefficient of –0.79. The x-axis is the time (milliseconds). The dominant arm force (right arm, solid line) and the non-dominant arm forces (left arm, dashed line) are plotted against the left y-axis (lbs). The overall correlation coefficient *ρoverall* (dotted line) is plotted against the right y-axis. *ρ*overall= the correlation coefficient for each force trial (from 2000 to 750 milliseconds before a TMS pulse)

**Fig. 5** Mean coefficient of variation (CV) produced by each arm and both arms in bimanual common-and dual-goal tasks. The data was presented as mean ± standard errors. \**P*<0.05

**Fig. 6** Our regression model showing a positive relationship between interlimb force variability and bimanual force variability during the common-goal tasks. The x-axis is the differences of force variability between the two arms (CVNon-dom – CVDom); The y-axis is the variability of total force from the two arms (CVSum)

**Fig. 7** No relationship was found between interlimb force variability and bimanual force variability during the dual-goal task. The x-axis is the differences of force variability between the two arms (CVNon-dom – CVDom); The y-axis is the variability of total force from the two arms (CVSum)