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Bilateral Transfer in Force Control is Affected by the Exercise Load Weight: An Implication for Rehabilitation of Stroke Patients

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Abstract

Aim: Two experiments examined the characteristics of bilateral transfer of force control in a sequential task from a dominant limb to non-dominant limb.

Setting: The experiments were conducted in a university research laboratory located in Texas, USA.

Population Sample: A total of 60 able-bodied participants took part in the study, with 30 participants for each experiment.

Method: Each experiment consisted of two groups; experimental group and control group. The participants in the control groups only participated in pre and posttests. The participants in the experimental groups learned a sequential task consisting of a low force control (10% of Maximum Voluntary Contraction (MVC), Experiment 1) and learned a sequential task with a higher force control (50% of MVC, Experiment 2). During the pretest, each participant completed the task with both hands prior to performing practice trials with his or her dominant hand only. A posttest was conducted one hour later.

Results: For both experimental groups, fine motor control significantly improved with the trained limb. Importantly, bilateral transfer of learning was only observed for the experimental group when learning with higher degree (i.e. amount) of force control (i.e. 50% MVC) in Experiment 2, and not for the experimental group in Experiment 1 (i.e. 10% MVC).

Conclusion: These findings indicate that bilateral transfer of force control is sensitive to the degree of the force production being learned. That is, a bilateral transfer of force control can only be found for a high degree of learning force, such as 50% of MVC in the present study, and not with a low degree of learning force (e.g. 10% of MVC). This may have an impact on learning and relearning motor skills in sports and rehabilitation setting.

Keywords: Intermanual transfer; Cross education; Sequential motor skill; Motor learning

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Introduction

Since the first report of bilateral transfer (also referred to as Intermanual transfer or cross-education) in motor skill learning [1], studies have focused on examining the direction of bilateral transfer [2,3], exploring the influence of task characteristics on bilateral transfer [4,5], applying bilateral transfer to enhancing the rehabilitation of stroke survivors [6], comparing the effect of physical practice and mental practice on bilateral transfer [7,8], determining if bilateral transfer occurs only when the training movements are executed [9], and finding neuromechanisms underlying bilateral transfer [10]. These studies have had direct and indirect implications in sport performance and in rehabilitation settings.

Research has consistently indicated that effects of learned skills transferred from a trained limb to an untrained homologous limb are task sensitive. For example, using a task to propel a small plastic disk with the index finger from a home position to a horizontal target Teixeira [11], found no significant bilateral transfer occurred for the contralateral hand. In another study Teixeira [4], found significantly positive transfer when they used a task to learn fine force control involved with a wrist-flexion movement. It should be noted that the fine force control was indirectly estimated by measuring movement spatial accuracy in Teixeira's study [4].

In a study requiring the learning of a specific fine force control, Yao et al. [5] required participants to exert four small isometric and constant forces (e.g. a sequential task) with given rhythms (e.g. total movement time =1500 msec, and 22.2%, 44.4% and 33.4% of the total movement time for segments 1 through 3; here segments were defined as two consecutive force exertions). The four rhythmic exertions were generated by abducting the index finger against an immovable force transducer button. In their study [5], acquisitions of timing and force control with the trained limb and transfer of the learning to the contralateral homologous limb were measured. While both timing and fine motor controls were significantly improved with the trained limb and the learning effect of the timing control was significantly transferred to the contralateral limb, the fine force control was not transferred to the contralateral limb. The authors [5] attributed the lack of bilateral transfer effect in the fine force control to the complexity of the task (learning both timing and force control) and the low degree of force control production (i.e. only 10% MVC).

The task used by Yao et al.'s study [5] consisted of both force-control learning and the component of learning goal movement times. Yao et al. [5] indicated that this task complexity could account for the lack of transfer. In a similar study by Park and Shea [12], participants were required to learn a task consisting of both timing and fine force control components. In this study they also found significant bilateral transfer of timing (relative and total time), but not in the case of force control. It is possible that the low degree (i.e. amount) of force may account for the absence of bilateral transfer in both of these studies.

According to the cross-activation hypothesis, bilateral transfer is due to the bilateral cortical activities caused by the single-limb training [13]. Research evidence has indicated that the degree of activation in the ipsilateral hemisphere is strongly affected by the force production of the muscle contraction [14], which in turn may influence the effect of bilateral transfer of force production according to the cross-activation hypothesis [13]. The 10% of MVC used in Yao et al.'s study [5] might be too small to cause co-activation in the ipsilateral hemisphere, thus resulting in a failure in terms of the bilateral transfer of force control. The aforementioned findings and assumptions warrant further attention and verification because rehabilitation specialist and/or coaches may need to know if the degree of force production should be considered in the practice settings to pursue effective bilateral transfer of force control. Therefore, the effects of the degree of force control on the bilateral transfer were examined in the current study in two separate experiments. The main purpose of Experiment 1 was to examine if the lack of transfer of force-control learning was due to the task complexity. It was hypothesized that bilateral transfer will not be affected by reduced task complexity and would not result in significant and positive transfer. The purpose of Experiment 2 was to examine whether an increased degree (i.e. amount) of force control would impact the degree of bilateral transfer. It was hypothesized that an increased degree of force control during learning would facilitate significant and positive bilateral transfer. The two hypotheses were made based on the research findings suggesting that the degree of activation in the ipsilateral hemisphere is strongly affected by the forcefulness of muscle contraction [14] and the cross-activation hypothesis [13].

Experiment 1

Methods

Participants

A total of 30 undergraduate students volunteered to participate in the study. All participants received course credit. The participants had no experience with the task and were not aware of the study's aims. Participants were randomly assigned into two groups, 15 participants in each group, experimental group (9 females, 19 to 25 years, M=20.15 yrs, SD=2.10) and control group (7 females, 19 to 25 (M=21.31 years, SD=2.40). All participants were right-hand dominant, as determined by the Edinburgh Handedness Inventory test. The University of Texas at San Antonio Human Participants Committee approved the study protocol. Informed consent was obtained from each of the participants before the experiment.

Task and apparatus

The participants learned a sequential skill which was similar to the one used by Yao et al. [5] with the only difference being that it did not having a timing control component. Instead, the participants in the current study were required to learn to produce a force production at 10% MVC. The participant abducted his or her index finger against an immovable button target (Figure 1) to exert four isometric forces at the targeted 10% MVC. The four forces were required to be exerted within 1500 msec (i.e. total movement time) with self-paced rhythm (i.e. there were no relative timing goals or external timing mechanism).

A button force transducer (subminiature load cell, Sensotec, Columbus, OH) was built into a wooden support. When the index finger was set in place and participant attempted to produce abduction, the transducer was pressed and force was recorded. The force was digitized (200 samples/s) by a MP 150 Data Acquisition System (Biopac Systems, Inc., Goleta, CA). The force signals were displayed on a computer monitor as visual feedback to the participant.

Surface Electromyography (EMG) were placed on the belly of left and right FDI to record muscles activity during each trial. The EMG signals were amplified (X1, 000) and digitized (2,000 samples/s) by the MP 150 Data Acquisition System. The surface EMG recordings of each individual's index finger muscle were taken for the purpose of keeping track of both index fingers' activities during practice (making sure there was no significant coactivity from the index finger on the non-dominant hand, while the one on the dominant hand exerted forces).

Procedures

The control group (Crt 10% MVC) only participated in pre and posttests. All participants sat and faced a 17-inch desktop computer monitor that was positioned approximately 1.5 m away at eye level. The monitor displayed the target force and the force exerted by the participant. The practiced hand was placed so that abduction of the index finger involved the metacarpophalangeal joint and the movements from other three fingers and thumb were prohibited (Figure 1). The unpracticed hand was resting on the ipsilateral thigh and adjusted to participant's comfort. The fingers of the unpracticed hand were not fixed. All participants were first tested with his or her MVC by abducting both the right and left index fingers against the immovable button target. The MVC from his/her index fingers was used as the reference for determining his or her 10% MVC forces.

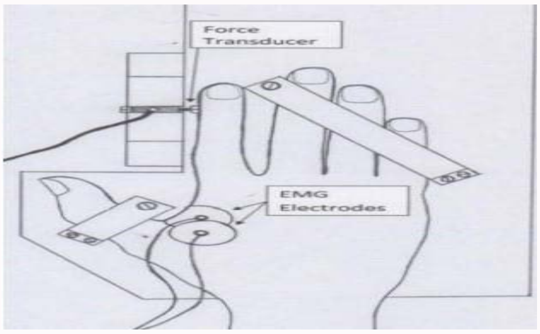

Figure 1: Illustration of the experimental setup.

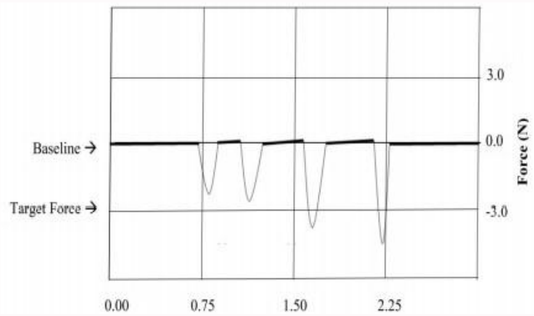

Figure 2: Example of visual feedback provided for force productions.

Practice phase

The participants in the experimental group (Exp 10% MVC) performed 60 practice trials with the index finger on his/her dominant hand (right hand) to learn the force-control production at 10% MVC in the practice phase. The participant received a 30-sec rest between each of the two adjacent trials within a block of 10 trials. In addition, a 2-min rest between any two blocks was provided to minimize any possible fatigue during trials. During each 30-sec break, the researchers provided the participants with visual feedback about their force production (Figure 2 for an example of the feedback regarding the force production).

Testing phase

The testing phase consisted of two tests, a pretest and a posttest. To avoid any learning effect from the pretest on the untrained limb (i.e. left hand), the pretest was conducted on the trained hand (i.e. right hand) only right after the experimenter explained and demonstrated the task for each participant. The posttest, however, was conducted on each hand (i.e. dominant and non-dominant hands) one hour after the practice. Each of the tests consisted of 10 no-feedback trials.

Data analyses

Before processing the following data analyses, all individual participants' Pre- and Posttest means of producing the 10% of MVC was calculated. If their force production was out of range (meaning that their mean production was ± 2 SD to the group mean) then it was considered an outlier. The entire data of the detected outliers were excluded from further analyses. As such, the results of one participant's data in the experimental group and two participants' data in the control group were excluded. Thus, there were 14 participants in the experimental group and 13 participants in the control group.

Acquisition phase

Absolute error of total force (TFAE) was calculated as the following:

$$TFAE = |F_1 - \text{goal F}| + |F_2 - \text{goal F}| + |F_3 - \text{goal F}| + |F_4 - \text{goal F}|$$

Where F_i = (the actual force production of each of the four sub-force exertions) and goal F is 10% MVC for each participant. The TFAE during the acquisition phase was analyzed with one-way repeated measure Analyses of Variance (ANOVA) (Practice Block) for the experimental group.

Test phase

The TFAEs during the test phase were analyzed for the trained limb and untrained lime separately. To examine the training effect, a two-way ANOVA (Phase x Group) with repeated-measures on Phase was analyzed for the right limb only (trained limb for the experimental group). There were two levels on the phase factor (i.e. pre- and posttests), and two levels on the group factor (i.e. experimental group and control group). To examine the transfer of the training effect from the trained right limb to the untrained left limb, a two-way ANOVA (Hand x Group) with repeated-measures on Hand was analyzed for both limbs with the posttest data. There were two levels on the hand factor (i.e. right and left limbs), and two levels on the group factor (i.e. experimental group and control group). All statistical significance was set at $P \leq 0.05$.

Results

Acquisition phase

MVC: The MVC of the right and left index fingers was analyzed with an Independent Samples t-test. No significant difference in MVC, t (38) =1.48, p=0.15, was found between the right and left fingers, M=33.88 N, SD=3.27 and M=32.45 N, SD=2.79, respectively.

Muscle activity during the task: EMG records taken during the practice trials were analyzed to illustrate if any significant muscle co-activations occurred on the untrained (left) FDI when the trained (right) FDI exerted force. The significant coactivity was defined as the EMG values of the untrained FDI during the acting period; these were beyond the range of the mean ± 3 SD of the EMG during the resting period. The results did not show significant coactivity on the untrained FDI. The results did not show any significant coactivation on the left FDI. That is, the average value of the rectified surface EMG on the untrained FDI during the period of the trained FDI exerting force was within a range of the mean ± 3 SD of the rectified surface EMG on the trained FDI during the resting period (i.e. the baseline).

Total force error (TFAE): The effect of block on TFAE was significant, F (5, 65) =4.01, $p<0.01$, partial $\eta^2=0.23$. A post hoc Bonferroni test on block indicated that TFAE was higher in blocks 1 to 3 than in blocks 4 to 6. In addition, there was no significant difference in any other pair comparison. See Figure 3 for the means and standard errors of TFAE.

Testing phase

Total force error (TFAE) of the trained limb (Right hand) with the pretest data: The main effect of phase was significant, F (1, 25) =14.36, $p<0.01$, partial $\eta^2=0.36$. The main effect of group was not significant, F (1, 25) =3.49, p=0.073, partial $\eta^2=0.84$. However, the interactive effect of the two factors was significant, F (1, 25) =6.67, $p<0.05$, partial $\eta^2=0.21$. The post hoc Bonferroni test indicated that the interaction was due to the fact that there were no significant differences in TFAE between pre- and posttests for the control group on the trained hand, but there was a significant difference for the

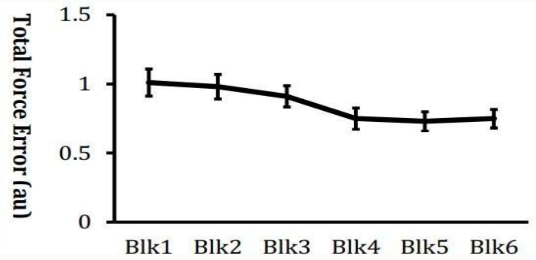

Figure 3: Means and standard errors of Total Force Absolute Error (TFAE) as a function of blocks of practice trials.

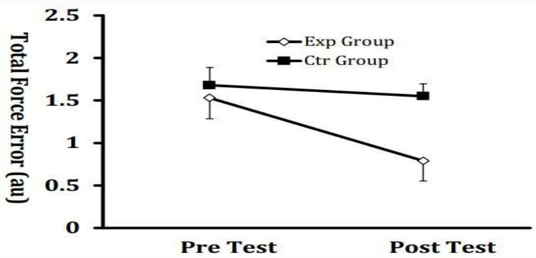

Figure 4: Means and standard errors of Total Force Absolute Error (TFAE) as a function of Pre and Posttests for the Trained Limb (Right Hand).

experimental group. See Figure 4 for the means and standard errors of TFAE for the test.

Total force error (TFAE) of both trained and untrained limbs with the post test data: The main effect of the hand was significant, F (1, 25) =6.91, p<0.05, partial η^2=0.21. The main effect of group was significant, F (1, 25) =4.41, p=0.05, partial η^2=0.88. However, the interactive effect of the two factors was also significant, F (1, 25) =4.75, p<0.05, partial η^2=0.16. The post hoc Bonferroni test indicated that the interaction was due to the fact that the right hand of the experimental group (i.e. the trained limb) outperformed the untrained hand. There was no significant difference in TFAE between the hands for the control group, but there was a significant difference for the experimental group. See Figure 5 for the means and standard errors of TFAE for the test.

Discussion

Experiment 1 examined if the reduced task complexity in the task used by Yao et al. [5], would result in a significant and positive bilateral control. Overall, training improved task performance from pretest to posttest. Moreover, posttest performance of the experimental group using the trained limb was significantly better than the control group during posttest. However, the training effect was limited to the trained limb only, and was not transferred to the untrained limb. In the experimental group, the performance of the untrained limb (i.e. left limb) was significantly poorer than that of the trained limb and no different from the performance of the left limb of the control group during posttest. Thus, the findings of Experiment 1 are consistent with Yao et al.'s study [5] but inconsistent with Teixeira's study [4], in which a significant bilateral transfer for the acquisition of the force control was found, although this transfer was much weaker than the timing transfer. We suggest that task differences might account for the disparities in results. Furthermore, the current study measured the force directly by monitoring force production during a force estimation task, whereas Teixeira's study [4] indirectly measured the force by accounting for spatial movement errors during aiming movements.

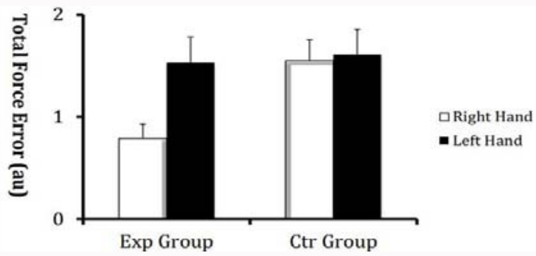

Figure 5: Means and standard errors of Total Force Absolute Error (TFAE) as a function of Posttest for Both Limbs.

The results of Experiment 1 tentatively suggest that the task complexity was not accountable for the lack of bilateral transfer of fine force control in Yao et al.'s study [5]. This finding left the degree of the fine force control, as we assumed, to be the potential factor to cause the lack of bilateral transfer in Yao et al.'s study [5]. This assumption was made according to the prediction of the cross-activation hypothesis [13]. According to this hypothesis, bilateral transfer is due to the bilateral cortical activities caused by single-limb training [13]. This hypothesis has been successful in predicting bilateral transfer with force control tasks [14-17]. Furthermore, evidence has indicated that the degree of activation in the ipsilateral hemisphere is strongly affected by the forcefulness of the muscle contraction [14], which in turn may influence the effect of bilateral transfer of force production. In the current experiment, only 10% of MVC was produced. This could be too small for causing co-activities in the ipsilateral hemisphere, thus resulting in a failure in terms of the bilateral transfer for the force control. Thus, with regard to the low force required in the present experiment (i.e. only 10% of MVC), an explanation for the absence of bilateral transfer can be derived from the cross-activation hypothesis [13].

In summary, the task complexity is not a major factor to affect the bilateral transfer of fine force control. Thus, this led to Experiment 2 in which the degree (i.e. amount) of force was examined to confirm if it played a significant role in the bilateral transfer of fine force control. It was generally hypothesized that bilateral transfer should be influenced by the degree of force control learning and the increased degree of force control (i.e. 50% MVC) would result in a significant and positive bilateral transfer.

Experiment 2

Methods

Participants

A total of 30 undergraduate students (16 females and 14 males) who did not participate in Experiment 1 volunteered for Experiment 2.

All participants received course credit, had no experience with the task, and were not aware of the study's aims.

The participants aged from 19 to 25 (M=21.31 years, SD=2.40) and were all right-hand dominant, as determined by the Edinburg Handedness Inventory test. The University of Texas at San Antonio Human Participants Committee approved the study protocol.

Informed consent was obtained from each of the participants before the experiment.

Task and apparatus

The participants learned the same task as Experiment 1 except

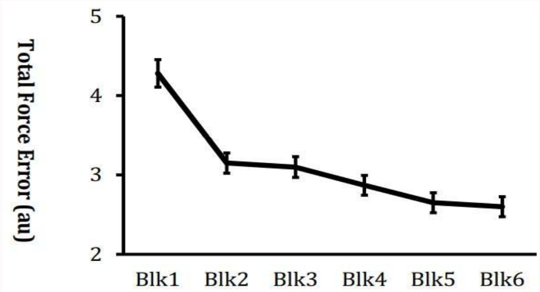

Figure 6: Means and standard errors of Total Force Absolute Error (TFAE) as a function of blocks of practice trials.

they were required to learn the sequential skill by exerting four small isometric and constant forces of their 50% MVC, instead of 10% MVC. As in Experiment 1, surface Electromyography (EMG) was placed on the left and right FDI muscles to record muscle activity during each trial. Prior to performing the subsequent data analyses, all participants' data was screened for outliers (i.e. the mean of dependent variables were out of the range of the group mean ± 2 SD). The entire data of the detected outliers were excluded from further analyses.

Procedures and data analyses

Same as in Experiment 1, the participants were randomly assigned to two groups, experimental group (Exp 50% MVC) and control group (Crt 50% MVC), 15 participants in each group. The control group only participated in pre and posttests. The procedures and data analyses in Experiment 2 were the same as in Experiment 1.

Results

Acquisition phase

MVC and muscle activity during the task: The MVC and EMG were similar to Experiment 1. Total Force Error (TFAE): The effect of block on TFAE was significant, F (5, 65) =10.45, $p<0.01$, partial $\eta^2=0.45$. Post-hoc Bonferroni test on block indicated that TFAE was higher in block 1 than in blocks 4 to 6. There was no significant difference in any other pair comparison. See the bottom panel of Figure 6 for the means and standard errors of TFAE for the practice blocks.

Testing phase

Total force error (TFAE) of the trained limb (Right hand) with the pretest data: The main effect of phase was significant, F (1, 25) =21.68, $p<0.01$, partial $\eta^2=0.51$. The main effect of group was not significant, F (1, 25) =2.93, $p=0.09$, partial $\eta^2=0.11$. However, the interactive effect of the two factors was significant, F (1, 25) =23.28, $p<0.01$, partial $\eta^2=0.48$. The post hoc Bonferroni test indicated that

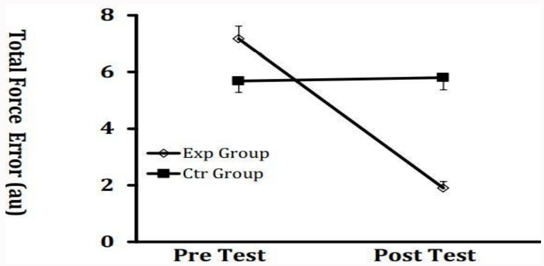

Figure 7: Means and standard errors of Total Force Absolute Error (TFAE) as a function of Pre and Posttests for the Trained Limb (Right Hand).

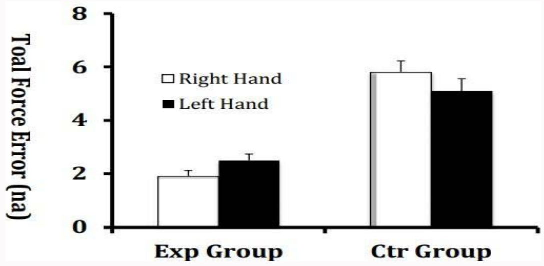

Figure 8: Means and standard errors of Total Force Absolute Error (TFAE) as a function of Posttest for Both Limbs.

the interaction was due to the fact that there was significant difference in TFAE between pre- and posttests for the experimental group only, but not for the control group. See Figure 7 for the means and standard errors of TFAE for the test.

Total force error (TFAE) of both trained and untrained limbs with the posttest data: The main effect of hand was not significant, F (1, 25) =0.03, $p=0.85$, partial $\eta^2=0.01$. The main effect of group was significant, F (1, 25) =22.00, $p<0.01$, partial $\eta^2=0.47$. There was no significant interactive effect of the two factors. See Figure 8 for the means and standard errors of TFAE for the test.

Discussion

This experiment examined the effect of the degree of learned force on the bilateral transfer of the sequential force control task. The results showed that after training, the trained limb improved significantly. The performance of the trained limb in the posttest for the experimental group was not only better than that in the pretest, but also significantly better than the control group during posttest. Furthermore, the training effect was also extended to the untrained limb as shown by significantly better performance of the untrained limb (i.e. left limb) for the experimental group than that of the control group. It should also be noted that there was no significant difference in the posttest between the right and left limbs for the experiment group, which is further evidence to indicate the positive bilateral transfer in Experiment 2. The results from Experiment 2 provide supporting evidence to indicate that the degree of force is an influential factor to determine the effect of bilateral transfer of the learned fine force control from the trained limb to the untrained limb. It should be noted that this bilateral transfer effect might not be caused by co-activities of the homologous muscles on the untrained limb as evident in Experiment 1, although the degree of the learned force increased to 50% MVC in this experiment (2), the EMG values of the untrained FDI during the acting period was not significantly co-activated. Thus, the bilateral transfer effect found in the current experiment may be from the central nervous system.

General Discussion

The aim of the current study was to determine the factors that caused the lack of bilateral transfer of fine force control in Yao et al.'s study [5]. The combined results of the two experiments in the current study indicated that the degree of force control was able to account for the lack of the bilateral transfer in Yao et al's study [5]. These results of the current studies are consistent with the cross-activation hypothesis [13].

As aforementioned, the cross-activation hypothesis attributes bilateral transfer to the bilateral cortical activities caused by single-limb training [13], and is especially successful in predicting bilateral transfer with force-control tasks [14-17]. However, significant bilateral cortical activities will not happen unless the degree of force (forcefulness of muscle contraction) applied on the training limb reaches to a certain level [14]. Therefore, in the present study positive bilateral transfer was found only when the degree of fine force control increased from 10% MVC to 50% MVC. As such, there must exist a necessary minimum amount of force production during learning to facilitate bilateral learning.

It should be noted that because the EMG on the untrained muscles were not significantly activated, although the degree of the fine force controlled raised up to 50% MVC (Experiment 2), the bilateral transfer found in the experiment might be due to the changes of motor cortexes at higher levels of the central nervous system, instead of at peripheral level. Due to the limitation of the experimental design, the current study is not able to determine the specific cortical area or areas that are accountable for the bilateral transfer, and can only speculated from the literature on CNS contributions. To this extent, findings from previous research indicates that the primary motor area [18] cingulate motor area [19], and premotor area and Supplementary Motor Area (SMA) [20] are all involved in generating bilateral transfer. Most recently, Ruddy et al. suggested that supplementary motor areas may play an essential role in bilateral transfer. Their finding is consistent with other studies regarding the role of SMA in movement control and bilateral transfer. For example, Tanji and Shima's study [21] found that SMA plays a prominent role in sequential movement planning (e.g. the task in the current study is in the category of sequential movement task), and a study by Perez et al. [22] found a high relationship between degree of bilateral transfer and activities in the SMA.

It must be pointed out that the current study only determined that a task with increased degree of fine force control (i.e. 50% MVC) and reduced task complexity (i.e. no timing control) resulted in positive bilateral transfer. However, it cannot conclude whether an increased degree of force control while maintaining the same level of task complexity as in Yao et al.'s [5] study (consisting of both timing and fine force control learning), will likewise lead to bilateral transfer. It is important to understand the nature of bilateral control for a task with both timing and fine force control because most sequential motor movements consist of the two components in daily life. Thus, further studies are necessary to clarify the contributions of each in task component.

Importantly, only the transfer of learning from the dominant to non-dominant limbs was examined in the current study. Thus, the authors can only draw conclusions regarding transfer from dominant to non-dominant limb. Thus, further research is necessary to examine the candidacy of bilateral transfer of fine force control from the non-dominant hand to the dominant hand. With that being said, a study by Stöckel & Weigelt [23] found that the bilateral transfer for a throwing-accuracy task (e.g. similar to the fine force control task in the current study) was more favored by having initial training with the non-dominant hand. In an earlier study, Thut et al. [24] reported a similar finding using a figure drawing task. Findings showed that spatial accuracy transferred best from the non-dominant to the dominant hand, whereas movement time transferred best from the dominant to the non-dominant hand. Therefore, the combined findings from these studies [23,24] tentatively suggest that bilateral transfer will occur if the non-dominant limb is the trained limb (i.e. having initial training with the non-dominant limb).

In summary, the current study hints that the degree of fine force control, accounted for the lack of the bilateral transfer of the fine motor control in Yao et al.'s study [5]. Additional research is needed to further examine whether bilateral transfer still exists when a task consists of both timing control and a high level of fine force control (e.g. 50% MVC) before we can fully understand the nature of bilateral transfer in learning a sequential task with both timing and force control. These findings will have impact on learning and/or relearning motor skills in sports and rehabilitation settings by optimizing practice schedules. These findings have clinical implications in terms of optimizing practice schedules. For example, bilateral transfer of a learned skill is often one of the key concerns and/or goals in rehabilitation training with stroke patients. Commonly, individuals suffering from a stroke are only able to voluntarily move one side of their body. Practitioners, who are treating this hemispheric disability, often have stroke patients practice their intact limbs with expectation or hope that this will facilitate rehabilitation of the limb of the affected side. Based on the current findings, a clinician would expect a significant bilateral transfer for a force-control when an appropriate degree of force control (i.e. 50% MVC) is applied. Future studies are also needed to investigate at the minimal level of force production necessary to facilitate bilateral transfer.

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