Single Limb Performance Following Contralateral Bimanual Limb Training

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***Abstract*—Recent studies on intermanual transfer of reaching movements suggest that this transfer is conducted over an "extrinsic" coordinate system. We hypothesize that training reaching movements in a force field with both hands at the same time, in the same position (bimanual grip) will be more beneficial in promoting transfer of the learned skill to the dominant hand than training the unimpaired limb on the same movements in the same force field since the representation of the movement should be invariant of the limb. However, unlike intermanual transfer, bimanual transfer has the potential to involve infinite number of actuator combinations, or joint configurations, interfering with consistent transfer. The efficacy of this method of transfer has implications for people with hemiparesis since the less-affected arm could potentially "instruct" the more-affected arm how to move. Here, we report on an experiment that evaluates and compares the skill transfer between limbs in a reaching task: 1) intermanual transfer (from the nondominant to the dominant hand) and 2) bimanual transfer (from a bimanual grip to the dominant hand) with healthy subjects. We used two methods from which to judge the transfer: performance in the presence of the force field or by errors made during "catch trials" when the forces were unexpectedly removed as subjects changed hands (known as after effects of adaptation). We found only a small amount of transfer (20% of that seen in the practiced limb) with both types of training, and surprisingly there was no significant difference in the movement accuracy between these two training methods. Moreover, the direction of the *after effects* supports the assertion that the nervous system generalizes these movements in an extrinsic coordinate system. Accordingly, the limb must experience the dynamics singularly in order to develop an internal model.**

***Index Terms*—Adaptation, force field, human motor control, internal model.**

I. Introduction

IN MANY instances of daily life such as opening a jar or transporting an object, we use both our hands cooperatively to accomplish the task. Many of the things we do with one hand we can do easily with the other, and when both hands work together the outcome can be better than if a single limb is used by itself. This concept becomes important to consider in cases where two people share the same task, or when an individual undergoes rehabilitation after brain injury and uses the less-affected limb to help in the recovery of the more-affected limb. While several researchers have focused on transferring skills from one limb to another [1], little is known about transferring skills learned bimanually to a single limb. This paper focuses on one such transfer in the intact nervous system, from a bimanual grip of a single handle.

Neuroplasticity and similarly, motor relearning are believed to be prominent mechanisms of recovery from hemiparesis due to stroke [2]. Coupling left and right motor commands through ipsilateral pathways is believed to be one of the mechanisms used to integrate the impaired motor pathways with the nonimpaired pathways. Similarly, coactivation of both arms at the same time might facilitate motor relearning. One issue that is not entirely clear is whether the underlying neural machinery allows for beneficial transfer of skills from shared bimanual tasks to a single limb—even in the healthy nervous system. There is much research pertaining to the ability of the central nervous system to control bimanual movements through callosal connections and alterations to the supplementary motor area and the primary motor cortex [3]. More investigation of healthy individuals can test for the underlying neural capability for transfer of skills.

Recent studies incorporating bilateral-assisted-training have noted a number of positive effects in clinical rating scales following long-term training using upper and lower extremity robotic devices for rehabilitation and for studying motor control [4]–[9]. One creative strategy is to *require* that both limbs participate. A driving simulator with an instrumented split-wheel for bimanual steering tasks provided an environment that required both hands to participate in force generation, which led to more appropriate forces from the hemiplegic hand [5]. Interventions poststroke have demonstrated improvements in measures such as functional performance, strength, range-of-motion, and clinical rating scales following bilateral training [10], [11]. Improvements in some spatiotemporal parameters of a movement task were noted during bimanual conditions in spastic hemiplegia [12]–[14]. However, improvements from bilateral interventions are not seen consistently across all individuals or tasks. Other bimanual coordination studies have characterized a wide variety of bimanual movements such as synchronous circle drawing tasks [15], temporal characteristics of bimanual targeted-reaching tasks [16], and grip strength [17] and found that coupling of movements did not provide a benefit to the impaired limb. The variation seen in results over these motor

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tasks involving transfer might be currently explained because the underlying functional mechanisms are not completely understood.

Indeed, in healthy individuals, the ability to transfer skills between limbs varies depending on whether the transfer is to the dominant or nondominant limb [18], [19] and on the type of skill [1]. For instance, a study involving a bimanual load-lifting showed no transfer of the learned anticipatory postural adjustment of the forearm [20]. Skills related to visuomotor rotations can be transferred from dominant to nondominant hand [21]. However, recent studies report only mild intermanual transfer of learned force patterns from dominant to nondominant limbs [1], [22]. In a study involving wrist-flexion movements, timing of a movement transferred well, while precise force control did not [23].

An alternative to transfer from one limb to another is to involve both limbs *together* during training, and test if these skills can be preserved when one hand lets go and the other limb has to perform on its own. We define bimanual training as learning an arm movement with both hands clasping a common handle, so that the arms are linked. Little is known about transferring skills gained by such bimanual-to-single limb transfer although such activity closely resembles therapeutic interventions for brain injured individuals.

The reasons are fairly obvious why one might claim that bimanual training is thought to benefit the single limb. Both limbs simultaneously experience similar endpoint kinematics and external forces so that at least part of the experience is available to the limb that will ultimately be performing by itself. Moreover, functional brain imaging studies have shown enhanced ipsilesional cortical activity in acute stroke survivors that use both limbs instead of just one [24], [25]. It would also seem logical that the brain would be able to retain the learning of skills using a bimanual grip and use them in situations when one limb lets go and a single limb has to perform on its own.

The opposite claim, that bimanual training may confound unimanual performance, is also reasonable if one considers the mechanical possibilities. Dynamics associated with two-handed tasks can be markedly different because the system is a closed kinematic chain. The motor redundancy of such a system allows for an infinite number of joint torque combinations, in contrast to unimanual grip where each action is associated with unique torques at each joint. For example, one can control such a system with the elbow flexors of one limb and the shoulder extensors of the other. A bimanual grip allows options for stabilization and an increased number of control options that are not available to the single limb increasing the complexity of the task.

The purpose of this paper is to characterize and compare bimanual and intermanual transfer of simple planar reaching skills learned in the presence of an externally applied force field. The two experiments in this initial study focused on target-directed reaching movements of healthy, right-handed subjects. The type of intermanual transfer investigated was restricted to transfer from nondominant to dominant limbs. Results show only mild transfer from bimanual grip to the dominant hand that was comparable to the amount of transfer from nondominant to the dominant hand, and that bimanual-to-nondominant-hand transfer and bimanual-to-dominant-hand transfer did not differ

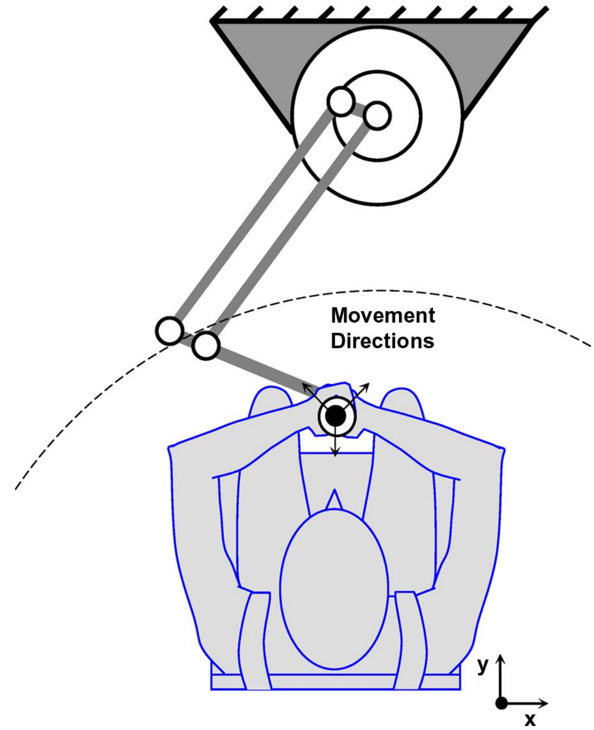

Fig. 1. Subject is seated at the planar manipulandum grasping the handle with a bimanual grasp. Forces are presented at the handle of the robot.

significantly. These results should guide future research in robot assisted training and rehabilitation.

II. Materials and Methods

A. Apparatus

All subjects used the two degree-of-freedom planar manipulandum shown in Fig. 1 described elsewhere [26]. Two brushed direct current torque motors (PMI model JR24M4CH, Kolmorgen Motion Technologies, Commack, NY) control the forces at the handle at the end of the links. Angular position is measured by rotational digital encoders (model 25/054-NB17-TA-PPA-QAR1S, Teledyne-Gurley, Troy, NY). A six degree-of-freedom load cell (Gamma 30/100 ATI, Garner, NC) fixed to the handle records interface kinetics, and rotational encoders recorded hand positions. Data was collected at 100 Hz.

B. Protocol

Thirty-four subjects with no known neuromuscular disorders participated in two experiments after giving informed consent in accordance with the Institutional Review Board standards of Northwestern University, Evanston, IL. Twenty-three subjects were enrolled in experiment 1 and 11 subjects in experiment 2. Three additional subjects performed experiment 1 but reported being left handed and were omitted from this analysis.

Our goal was to address whether the motor system could adapt and transfer skills after training in a commonly-used vector field of robot-applied forces. Targeted-reaching movements were performed with constant exposure to the so-called "curl" force field, governed by

$$\mathbf{F} = \begin{bmatrix} 0 & \lambda \\ -\lambda & 0 \end{bmatrix} \dot{\mathbf{x}}$$

where $\mathbf{F}$ is the vector of forces, $\dot{\mathbf{x}}$ is the vector of instantaneous velocity, and λ is the gain, set to a value of $20\ \mathrm{N \cdot s/m}$ for this experiment. The magnitude of force depended linearly on hand speed directed perpendicular to the instantaneous direction of movement.

The subjects were seated at the robot with their trunks restrained. A horizontal screen was placed over the subjects' hands so that the workspace of the robot and targets were visible as a projection on the screen. A small dot projected on the screen corresponded to the position of the handle. Each subject was instructed to move this small dot from a starting target to a visually-displayed end target 10 cm away. The initial target was always placed in the center of the workspace directly in front of the subjects 45 cm away from the robot, and each new target was in one of three directions (Fig. 1). The pseudo-random sequence of movements was limited, however, to a small rectangular space 28 cm wide by 38 cm deep. The starting target was directly in front of the subject to preserve symmetry for the subjects that learned the field with a bimanual grip. There were three total end targets, spaced 120° apart starting at 30°. The end targets appeared randomly among these three directions. Subjects were instructed that they could initiate movements at a self-determined time after the target appeared. We controlled for a peak speed of 0.4 m/s by giving subjects feedback at the end of each movement using colored dots and auditory tones. These let subjects know if they were going too fast, too slow, or within a range of ±0.05 m/s of the requested movement speed. Consequently, subjects' speeds remained roughly constant across the entire experiment. To prevent fatigue, subjects were instructed to rest anytime they chose.

Our approach involved two complementary experiments. The first experiment compared right limb movements after left limb training or bimanual training. The second experiment compared right and left limb movements after bimanual training. Both experiments are described in detail below.

Experiment 1 looked at the influence of either bimanual or nondominant training on the dominant (right) hand. We used two methods to evaluate this influence. First, the subjects continue to function in the presence of the force field. This would demonstrate the subject's performance as they transfer their skill to the right limb. A second method of evaluating the influence of training is to unexpectedly remove the forces as the subject switches to the right hand at the end of training. This reveals the after effects of adaptation. Any curvature of the after effects should reflect nature of the learned representation in the nervous system. Hence Experiment 1 involved four groups of subjects in a two-by-two-factor analysis: two types of training (bimanual and left limb) and two types of evaluation (performance in the field and after effects).

Trials followed the structure shown in Fig. 2. Subjects performed baseline movements with null forces (66 movements). then experienced an initial, intermittent exposure to the force field, then trained using either their nondominant hand or a bimanual grip in the presence of the force field (510 movements), then switched to the test condition for evaluation of transfer (60 movements), and then experienced no forces as the effects of training washed out (75 movements).

Experiment 2 was a follow-up study using similar experimental conditions, but examined the influence of bimanual training on how each limb performed alone. A single group of 11 subjects trained bimanually, and we evaluated their performance on each limb separately. First, training occurred in the same curl force field with the same reaching movements using a bimanual grip to the same set of targets as presented in experiment 1. Subjects were evaluated with one hand (15 movements) following training, then switched back to bimanual training for a training refresher (15 movements), followed by a test on the other hand (15 movements). There was no washout period. The testing order of the two limbs was randomized among the subjects. For these subjects, we chose to only test the performance of subjects in the presence of the field.

C. Data Analysis

Each subject's motor performance was accessed through a simple kinematics evaluation assuming that straight line movements from the starting position to the target were the movements the subjects intended to make. Quantitative evaluations of movement error compared a subject's initial movement direction with a straight line path from the starting target to the ending target. This initial direction error was calculated using the point at which the subject reached 30% of the distance to the target. Movement accuracy was quantified by means of an infinity norm parameter. The maximum distance between the average path taken and the desired path was measured for each subject.

In order to assess the learning of subjects evaluated in the presence of the force field (Groups 1 and 2 of Experiment 1 and all subjects in Experiment 2), we compared the first 15 to the last 15 trails of training. To assess interlimb transfer, the 15 trials of the initial exposure phase before training were compared to the 15 trials immediately following training.

In order to assess the learning of subjects evaluated by removing the forces to test for after effects (Groups 3 and 4 of Experiment 1), we compared the 15 trails of the unperturbed baseline (with no forces) to the 15 randomly-presented trials at the end of the training phase that were catch trials where force was unexpectedly removed. To assess interlimb transfer, the 15 unperturbed baseline trails for the right hand before training were compared with the first 15 washout trials after training where force field was removed.

A paired t test with an alpha-level of 0.05 was conducted to evaluate if significant learning and transfer occurred for each subject, and a standard t test ($\alpha = 0.05$) was used to compare the transfer and learning curves of each group of subjects. To compare the learning curves of the two different types of training (left-handed and bimanual) along with the two modes of testing (performance in the field or evaluating after effects of training) we used a two way analysis of variance (ANOVA). A

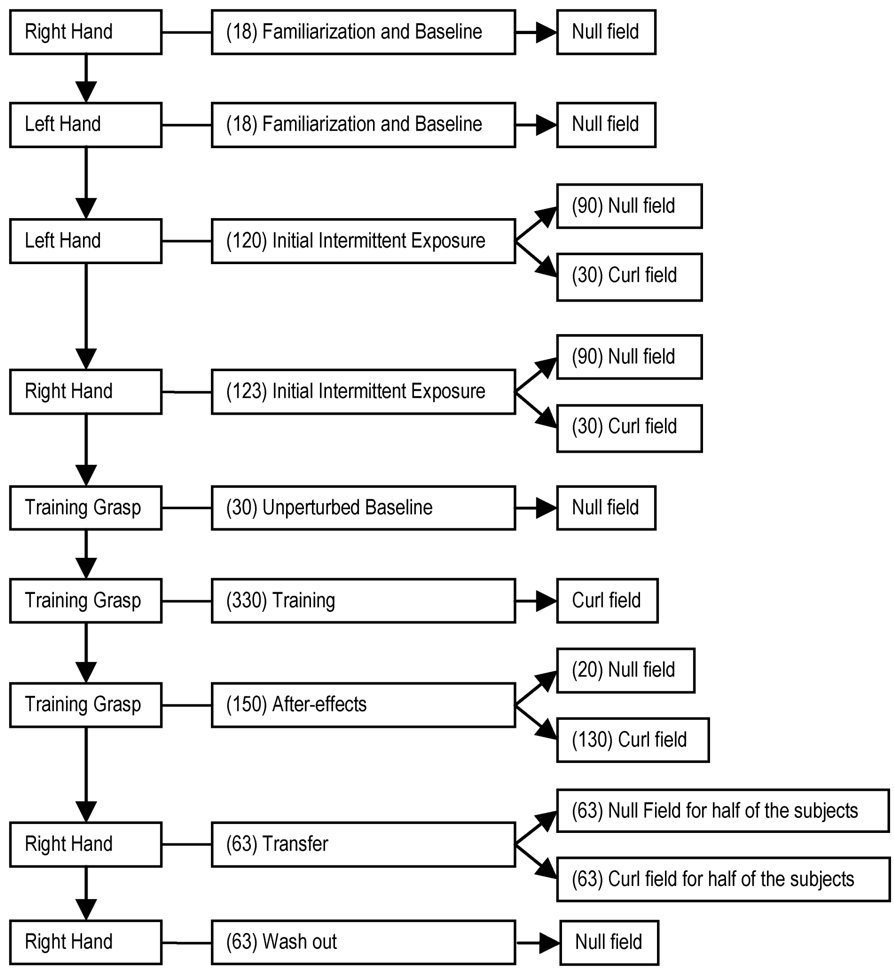

Fig. 2. Outline of main procedure for Experiment 1. The experiment began with a familiarization and baseline phase for both hands. Half of the subjects trained in the curl field with their left hand while the other half trained with a bimanual grip. Transfer occurred in a similar manner; half of the subjects that trained bimanually, made reaching movements with their right hand in the curl field while the other half transferred in a null field. Similarly, those who trained with their left hand were split in the same manner for transfer.

one-way ANOVA was used to test for a difference in amounts of learning for the follow-up group.

III. Results

Before focusing on the transfer of learning to a single limb, the effects of practice showed direct evidence of learning. As a group, subjects training with left (nondominant) limbs [Fig. 3(a)] and subjects training bimanually [Fig. 4(a)] tended to reduce their errors by making straighter movements to the target over the course of training ($p < 0.05$ for both nondominant and bimanual learning curves). However, in both groups, two of the subjects did not significantly learn during the training phase. The lack of significant learning is represented by the dashed lines connecting the subjects' data in Fig. 3(a) and Fig. 4(a).

Other evidence of learning is present as after effects shown during catch trials, where, for randomly presented trials, forces were unexpectedly turned off. Significant after effects were present for all left hand training subjects (Fig. 5(a); $p < 0.01$), but were not present in bimanual training (Fig. 6(a); $p > 0.05$). Only two subjects that practiced with a bimanual grip showed significant after effects.

In the case of the transfer of learning, training with the left limb led to no significant transfer of skills to the right limb as a group (Fig. 3(b); $p = 0.54$). Interestingly, the two subjects that did not significantly learn with the left hand [dashed lines in Fig. 3(a)] were the same subjects who generated very large errors when they switched hands [solid positive sloped lines in Fig. 3(b)]. Transfer to the right hand became statistically significant when these two subjects were omitted from consideration ($p = 0.0005$).

Significant transfer to the right hand occurred after bimanual training in the field [Fig. 4(b); $p = 0.0005$]. Two of the five subjects that trained with a bimanual grip did not significantly learn although significant transfer occurred for the group. Upon omitting the two subjects that did not significantly learn, the average change in error for right transfer decreased from $-13.5 \pm 3.5°$ for all five subjects to $-15.3 \pm 4.8°$ for the three subjects that successfully learned the movements using the bimanual grip.

After effects from the transfer to the right hand after training with the left hand revealed significant transfer as a group (Fig. 5(b), $p = 0.01$). However, only two of the six subjects showed significant transfer individually. When measuring the after effects, significant transfer to the dominant hand occurred

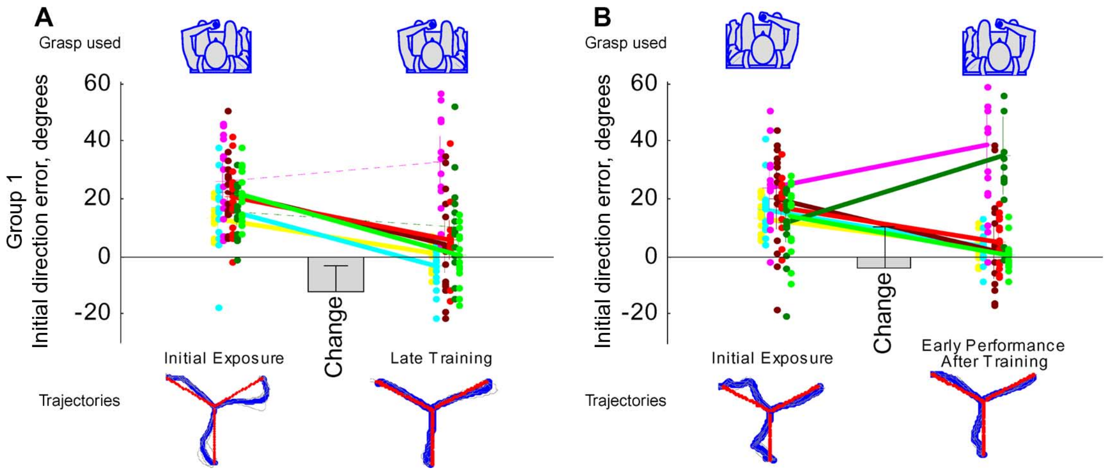

Fig. 3. Measures of initial direction error for left hand training are shown for testing training (A) and transfer (B) performance. Each dot represents a subject's data for a specific trial. Each column of dots within a plot represents a subject; vertical lines show the confidence interval for that subject. The diagonal lines indicate the learning curve for a particular subject. Solid diagonal lines represent significant learning took place; dashed diagonal lines indicate the opposite. Associated with each phase of the experiment are diagrams depicting the grasp and representative trajectories. $(N = 7)$.

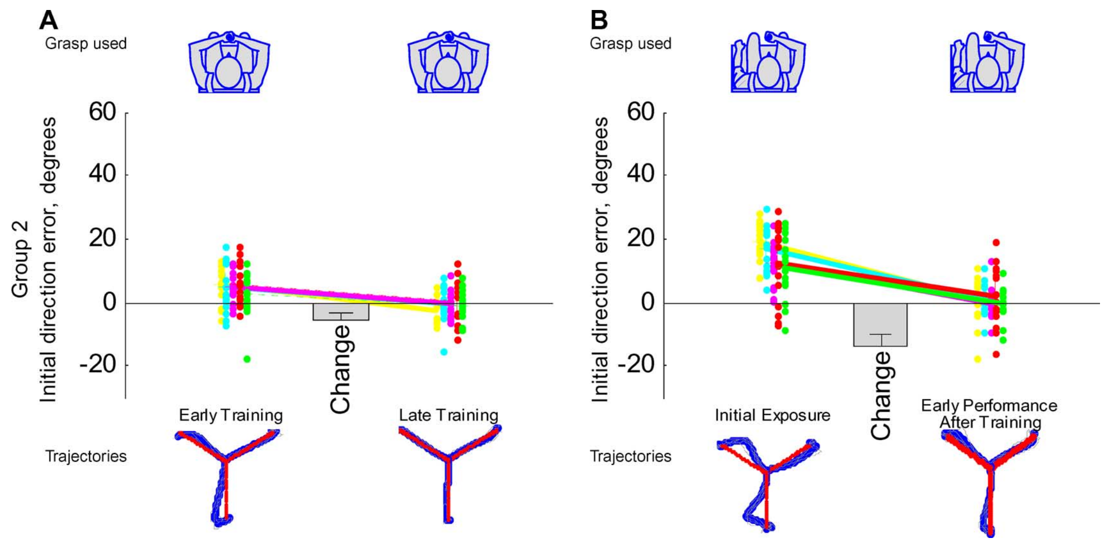

Fig. 4. Measures of initial direction error for bimanual grasp training are shown for testing training (A) and transfer (B) performance. The data are presented in a similar manner to Fig. 3. $(N = 5)$.

for the subjects that trained bimanually (Fig. 6(b); $p = 0.043$). These after effects in the transfer were not significant for any of the individual subjects, but as a group they were significant, potentially indicating a mild transfer of learning from bimanual training. However, this weak result should be interpreted with caution; it may have only arisen as an artifact of the statistical methods.

The most compelling question is whether there is a difference in transfer between the bimanual training and intermanual training. Results were not significantly different either in the performance in the presence of the force field or in the after effects ($p = 0.70$ when evaluating the differences between the left-handed and bimanual training groups of both evaluation methods). Additionally, there was a significant difference in transfer between the two evaluation methods ($p = 0.01$).

As a follow-up, Experiment 2 explored transfer to *both* the left and to the right hand after making these reaching movements in the field with a bimanual grip. This experiment mimicked the part of Experiment 1 where the subjects trained bimanually in the field. We compared dominant and nondominant limb movements after bimanual training. We were interested in determining if skills could transfer equally to those hands.

Nearly all subjects significantly adapted, indicated by a significant reduction in error during training. There were three subjects who did not significantly learn, but overall as a group, significant bimanual learning occurred (Fig. 7(a); $p < 0.01$). A brief exposure to the field on the left and the right hand displays the subject's unfamiliarity with the field (Fig. 7(b) and (c), left columns). Transfer to both the nondominant and dominant hand occurred similarly (Fig. 7(b) and (c); $p < 0.01$ for both hands) yet transfer to the dominant hand was performed with less error than to the nondominant hand. Regarding the difference in the ability to transfer skills to either the left or right hand, we failed to detect any difference—the similarity in transfer for both was striking. However, performance on the right limb showed final errors that were not significantly different than zero ($p > 0.05$).

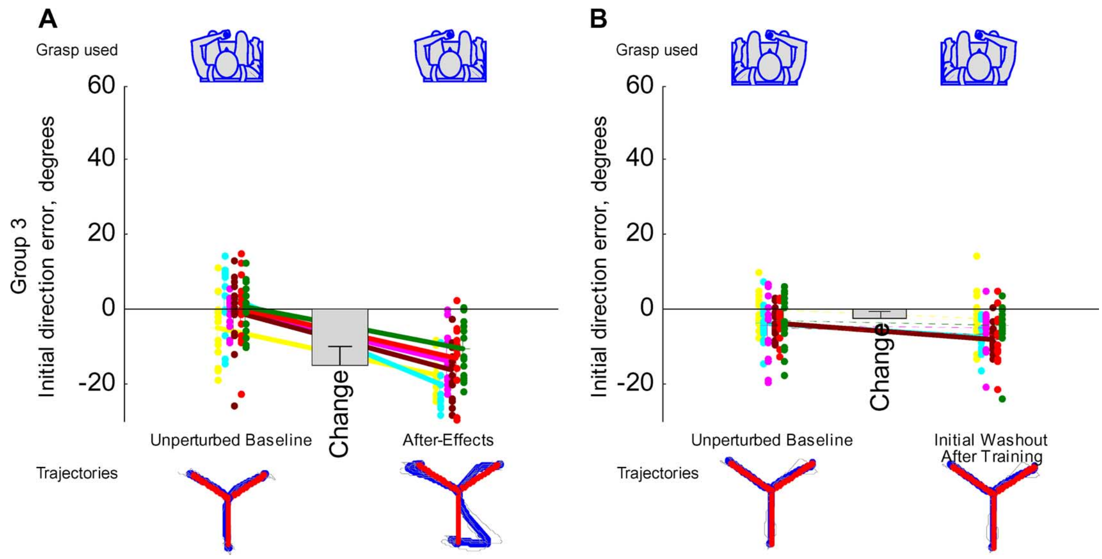

Fig. 5. Measures of initial direction error for left hand training are shown for testing training (A) and transfer (B) using after effects. For left hand training, the baseline phase was compared to the after effects on the left hand after training. Similarly, the transfer to the right hand was tested in the same manner. The difference between the phases is represented by the bar plot labeled "Change." $(N = 6)$.

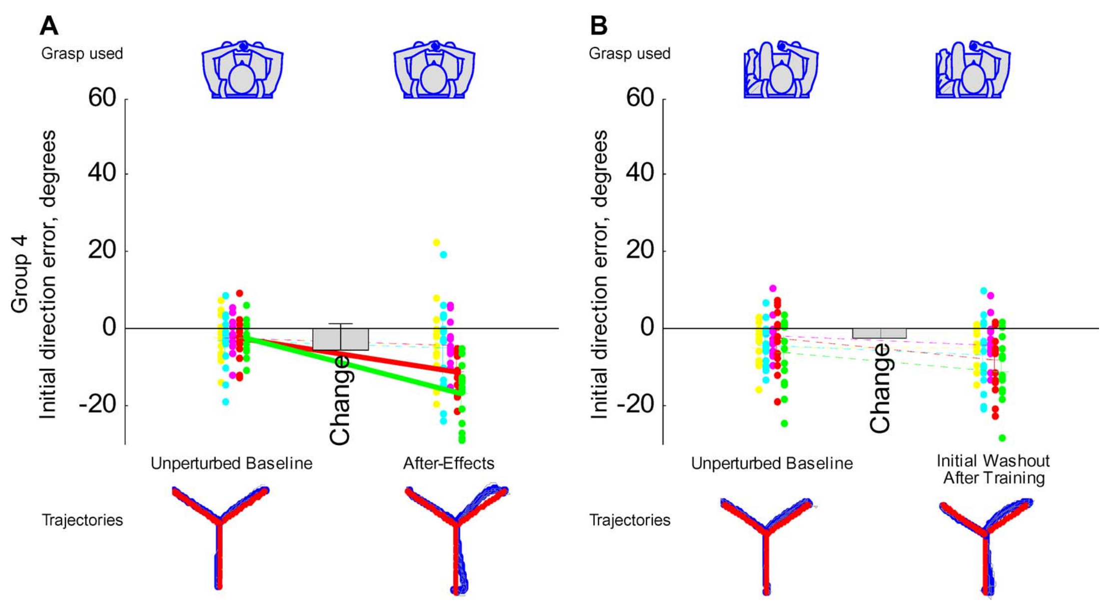

Fig. 6. Measures of initial direction error for bimanual grasp training are shown for testing training (A) and transfer (B) using after effects. The data are presented in a similar manner to Fig. 5. $(N = 5)$.

In contrast, the left arm began with more error than the right arm began with and ended with significant error $(p < 0.005)$.

IV. Discussion

This study on healthy right-handed people provides evidence that skills learned while practicing with a bimanual grip generalize (or transfer) to both the dominant and the nondominant arms. This study produced several main findings. First, bimanual training of reaching movements in a novel force field produced transfer to the dominant hand that was no better than transfer to the dominant hand after nondominant training.

SA second finding was that both intermanual and bimanual transfer appear to generalize to the dominant arm in the same way that suggests the use of an extrinsic coordinate system, because subjects' after effects curved in the same direction no matter what limb(s) were being used.

A third finding of this study is that bimanual training of reaching movements produced transfer to the nondominant hand and dominant hand with similar strength. However, only right-handed subjects were tested in this study, and data may differ in the left-handed and ambidextrous populations. We also only tested left-to-right and not right-to-left transfer, which may also differ.

Our findings are tempered by two methodological limitations. First, our technology did not permit us to have a group that experienced mirror-coupling of hand interactions in the bimanual task. The parallel-coupling of this initial study (hands interlaced on a single handle) may be less conducive for the

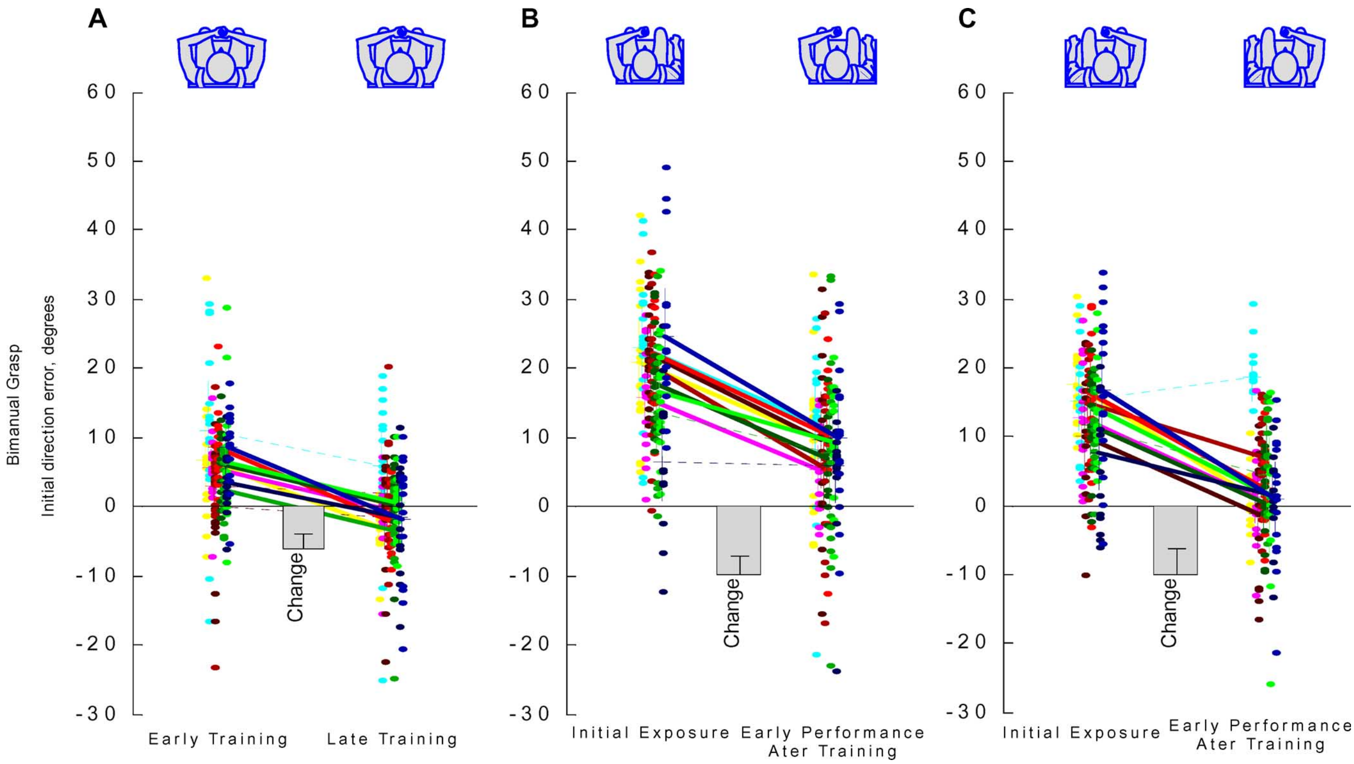

Fig. 7. Initial direction error for bimanual performance in the field for the follow-up Experiment 2. (A) Learning for bimanual training in the presence of the force field. (B) and (C) represent the performance in the presence of the field of the left and right hands, respectively before and after bimanual training. Similar to previous figures, the change in error before and after training is represented by the bar plots. ($N = 11$).

nervous system to form a representation of the reaching task during learning. Robotic technology, such as two coupled robots, would allow for mirror-type movements, and might reveal a much better transfer of skills when one hand lets go and the other has to perform the task on its own. Second, our technology did not allow a measurement of individual hand forces (only the resultant) or muscle activity using electromyography (EMG). If instrumented separate handles were used for this reaching task, the contact forces of both hands could be measured as the limbs share the burden of learning to move [27]. Such a system would reveal bimanual co-contraction if the limbs oppose each other to increase stiffness. Further testing using EMG could distinguish which of various muscles act in novel arrangements to accomplish the requirements of resultant force and hand impedance. The passive inertial properties of two limbs coupled are another source of impedance. It is important to note that only two subjects that practiced with a bimanual grip showed evidence of significant after effects, suggesting that the added inertia of an extra limb might have contributed impedance making it less necessary to learn an internal model that predicts and counteracts the force field.

In spite of many known differences between dominant and nondominant limbs mentioned in the literature [1], [18], [19], the left and right arms each effectively received a similar benefit after bimanual training. Learning was comparable to that seen previously in experiments on the right (dominant) limb [28]. The dominant hand in Fig. 7 appeared to perform better than the nondominant hand after training, but the overall improvement from both hands was equivalent. Because the limbs visited the same states and experienced the same forces, there is the possibility that they shared an equivalent learning effect—one arm does not learn all of the skill while the other rides along. Instead, each limb shares the learning effect in roughly equal amounts.

These results also support other studies [1] by showing that the nervous system generalizes tasks using an extrinsic (i.e., Cartesian) coordinate system rather than an intrinsic (i.e., joint) system. Since trajectories on the right and the left hands both showed a similar orientation, knowledge of the field transferred in an extrinsic manner. This also bodes well for rehabilitation techniques that want to influence one limb to help the recovery of function in the other, since this assumes that the system possesses a representation of the system dynamics that is invariant to the limb.

Nevertheless, the apparent extrinsic (Cartesian) representation that this and other intermanual studies demonstrate is in conflict with other studies that have presented evidence that the functional form of internal models is a mapping between intrinsic coordinates (i.e., joint angles) and the intrinsic forces (i.e., joint torques) [29], [30]. However, because of the extrinsic transfer of skills observed here and in other studies, the nervous system must also establish and exploit a relationship between extrinsic endpoint coordinates and forces. One possibility is that there are multiple, simultaneous, neural representations of the external world. Such representations may compete in tasks such as the one of this study, resulting in the mild transfer in a coordinate representation that conflict with unimanual training studies.

The two subjects that did not successfully adapt to the force field with their left hand in experiment 1 (dashed lines in Fig. 3, left) were the same subjects that generated very large errors when they switched hands (Fig. 3, right). Perhaps this finding builds upon those of a previous study by Criscamanga–Hemminger and colleagues [1] stating that the nondominant-to-dominant transfer does not occur. Here, we have shown evidence that some individuals may not be able to generalize skills learned from training with the nondominant hand. We suggest that for some subjects the controller serving the nondominant limb may have difficulty learning this and similar reaching tasks. Their nervous system might use a coordinate system that is not consistently appropriate for motor adaptation on that limb or transfer of these tasks to the opposite limb.

The evidence of after effects results in Experiment 1 refute the unlikely possibility that a bimanual system might simply contend with the external forces by co-contracting to stabilize the arms. Such after effects suggest that bimanual training mildly promotes learning that facilitates the performance after one limb lets go. The reduction in the strength of transfer when testing with after effects is potentially due in part to our methods. More specifically, since we measured the after effects on the right hand as the first 15 movements after training in the null force field, those after effects might have been reduced due to washout.

It remains to be seen if these bimanual influences in healthy are effective when applied to the restoration of function in stroke or other neurological injury. Nevertheless, the results here suggests that it should be possible to heighten other adaptive training techniques [31]–[34] by combining them with bimanual training to assist the nervous system when learning new movements.

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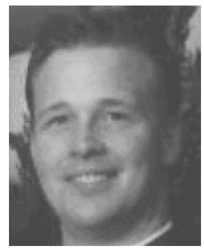

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