

**HANDEDNESS, LIMB SELECTION, AND REACH CONTROL: A TEST  
OF THE DYNAMIC DOMINANCE HYPOTHESIS**

A Dissertation

by

WON DAE KIM

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2008

Major Subject: Kinesiology

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Approved by:

Chair of Committee,	Carl Gabbard
Committee Members,	John Buchanan
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**ABSTRACT**

Handedness, Limb Selection, and Reach Control: A Test of the Dynamic

Dominance Hypothesis. (December 2008)

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Chair of Advisory Committee: Dr. Carl Gabbard

This study examined the generalization of the Dynamic Dominance Hypothesis (DDH) in regard to limb dominance, limb selection, and limb action. This study was inspired by the finding that limb selection changes from dominant-arm to nondominant-arm occur around an object position of 80° for right-handers and 100° for left-handers after passing the body midline (90°) into contralateral hemispace.

For Study 1 and Study 2, 10 right-handed and 10 left-handed adults participated and reaching with the right and left arms of right- and left-handers was made to each of nine targets using free-choice and forced-choice paradigms. The purpose of Study 1 was to determine the relationship between limb selection and the DDH among both handedness groups. Thus, Study 1 addressed the following questions: *Can the DDH explain why people select their nondominant hand for reaching into their contralateral hemispace? Do predictions of the DDH hold for right- and left-handers?* Our results suggest that control efficiency with regard to a reduction in degrees of freedom in reaching movements seems to be a more fundamental cause for the limb selection

phenomenon rather than the DDH. Also, our data reveal that kinematic differences between right- and left-handers with regard to utilization of joints for reaching explain limb selection differences between both handedness groups. The aim of Study 2 was to extend generalization of the DDH using a wide range of movement speed. Thus, Study 2 addressed the following question: *Do propositions of the DDH hold for a wide range of speeds?* Our data indicate the DDH does not hold for either slow or fast speed in reaching movements. Rather, a change in kinematics with regard to utilization of joints in reaching movements is associated with movement speed.

Considered together, our data indicate that the DDH is an inadequate explanation of differences in limb selection, limb dominance (handedness), and limb action (speed). Rather, our findings with regard to control efficiency seem to be more fundamental and justified explanations for limb differences in the control of reaching based on the context of our task.

**DEDICATION**

To my father Kim ja Young ja Ho ja, my mother Yoon ja Moon ja Ga ja, and  
my wife Hye-Joo  
for their unconditional love and support.

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## CHAPTER I

### INTRODUCTION

Limb selection for reaching is a key factor in assuring goal attainment, with hand preference being acknowledged as a prominent underlying feature. The notion that hand preference in general is a biological-based 'invariant' trait has been questioned in light of evidence suggesting that this phenomenon can be modified by attentional information derived from particular task demands (Gabbard, Iteya, & Rabb, 1997; Gabbard, Rabb, & Gentry, 1998, 2001; Hellige & Kee 1990; Peters 1995; Stins, Kadar, & Costall, 2001; Verfaellie, Bowers, & Heilman, 1988). In the quest to better understand the determinants of limb selection for simple reaching and grasping, our lab has reported consistent observations of participants choosing the limb closest to the object, regardless of object position in hemispace (Gabbard et al. 2001; Gabbard & Helbig 2004; Helbig & Gabbard 2004). In addition to concluding that this finding is in contradiction to more traditional views of motor dominance, we also found no reason to believe (via specific experiments) that perceived comfort or a hemispheric bias favoring use of the hand on the same side as the stimulus, was driving limb selection. However, none of these factors are enough to explain the finding that a limb transition from a dominant arm to a non-dominant arm among right-handers occurs around 70° after passing the body midline (90°) into contralateral hemispace.

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This dissertation follows the style of *Journal of Motor Behavior*.

While our previous work has addressed such things as object proximity, comfort and hemispheric bias as contributing factors to limb selection, a detailed examination of the kinematics of limb selection has received little attention. Although studies of the biomechanics of reaching rarely give attention to selection, there are hints in the literature that interlimb differences, in torque control and kinematic factors related to control efficiency, may contribute significantly to limb selection (Kim, Gabbard, Ryu, & Buchanan, 2007, Stins et al, 2001). In addition to the kinematic and kinetic explanations, a more contemporary perspective focuses on interlimb differences with the general idea that the two arms are differentially specialized for actions (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002, 2003). In reference to interlimb differences, one of the most recognized contemporary theories is the *Dynamic Dominance Hypothesis* (DDH) (Sainburg & Kalakanis, 2000). Although the DDH has been proven to be a reasonable explanation for differences in dominant and nondominant arm control, the hypothesis has not been generalized as a theory of limb selection.

Therefore, the present study focused on the generalization of the DDH in regard to *Limb Dominance*, *Limb Selection*, and *Limb Action*. The following is a brief background of the relevant areas of research associated with this dissertation, namely: handedness and limb dominance, limb selection, and the dynamic dominance hypothesis and its limitations.

### **Handedness and Limb Dominance**

Handedness is the most distinct feature of brain lateralization and specialization, and is defined by the unequal distribution of motor skill between the left and right arms. Although enormous efforts and studies to reveal the features of handedness have been

performed, understanding handedness still remains a fundamental question in motor behavior. However, there is no doubt that handedness is the outcome of biological and functional asymmetry in the human brain. With regard to specific characteristics of functional hemispheric differences in the control of upper limb movements, more than a century ago, Woodworth (1899) suggested a model which has come to be known as the *two-component model* because the control of speeded limb movements was hypothesized to entail both a central and a feedback-based component. The model has motivated new paths of understanding handedness in terms of open-loop or closed-loop processes. More specifically, this hypothesis describes the acceleration phase of goal-directed movements as indicating planning or programming of movements (open-loop control), and the deceleration phase as reflecting changing of direction for accuracy through sensory feedback processes (closed-loop control) (Woodworth, 1899). It is generally thought that each of these two control modes is associated with each hemispheric side. Thus, the left hemisphere is more specialized for open loop processing or movement preplanning, which is dependent on motor programs (Haaland, Prestopnik, Knight, & Lee, 2004). For goal-directed reaching, the left hemisphere is more specialized for ballistic movements that are more dependent on planning and less dependent on direct sensory feedback (Haaland & Harrington, 1994). Thus, the left hemisphere plays an important role in controlling various motor skills when greater planning is required (Hermsdörfer, Ulrich, Marquardt, Goldenberg, & Mai, 1999; Schuster, Krams, Rushworth, & Passingham, 2001; Kim, Ashe, Hendrich, Ellermann, Merkle, & Ugurbil, 1993). In contrast, the right hemisphere is more associated with feedback processing that tends toward controlling based upon closed-loop

processes. That is, the right hemisphere plays a primary role in controlling sensory feedback.

As another of the views of handedness, Liepmann (1905) proposed that handedness emerges because the *dominant hemisphere*, reflecting the hemisphere that is contralateral to the dominant arm, is used to plan movements of both arms. According to this idea, performance disadvantages of the nondominant arm result from interhemispheric transmission delays associated with dominant hemisphere commands for nondominant arm movements (Derakhshan, 2006). This model of handedness predicts performance advantages of the dominant arm for all aspects of motor control and coordination. Thus, this view asserts that the trait of handedness is basically an invariant feature characterized by superiority of the dominant limb (Bradshaw et al., 1992; Grouios, 2006), which is the right for the vast majority of the population. Indeed, a general review of motor behavior indicates that right-handed individuals typically execute aiming movements with better speed, smoothness, consistency and accuracy when performing them with their right hand (Bradshaw et al., 1992; Grouios, 2006). In essence, left-handers are more variable and “less lateralized” in various aspects of functional asymmetric behavior compared to right-handers. Underlying this general observation is evidence that the left and right cerebral hemispheres do not handle all aspects of visual information processing with equal ability (Hellige, 1995; Kosslyn, Andeson, Hillger, & Hamilton, 1994). This observation includes an array of motor tasks, including reaching, that compared right- and left-handers (e.g., Bestelmeyer & Carey, 2004; Brysbaert, 1994; Curt, Maccario, & Dellatolas, 1992; De Agostini, Paré, Goudot, & Dellatolas, 1992; Gabbard et al., 1997; Hellige, Bloch, Cowin,

Eng, Eviatar, & Sergent, 1994; Schmidt, Oliveira, Krahe, & Filgueiras, 2000). However, a more contemporary perspective focuses on interlimb differences with the general idea that the two arms are differentially specialized for actions (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2003). More specific, this notion proposes that each hemisphere limb system is specialized for selecting and controlling different features of a reaching action. For example, even among strongly lateralized right-handers, the non-dominant left limb is advantageous in specific situations.

### **Limb Selection**

One of the key elements of limb dominance is the selection of a specific limb to accomplish a goal. In regard to limb selection, data from our lab indicates that the vast majority of individuals will switch hands for simple reaching and grasping based on the proximity of the object. That is, limb selection changes from dominant right-arm to non-dominant left-arm in strongly lateralized right-handers around an object position of 80° after passing the body midline (90°) into contralateral non-dominant hemisphere (Gabbard & Helbig, 2004; Helbig & Gabbard, 2004). Other researchers have demonstrated similar findings across an array of selection tasks (Leconte & Fagard, 2006; Mamolo, Roy, Bryden, & Rohr, 2004, 2005; Stins et al., 2001; Teixeira, & Okazaki, 2007). Explanations of this phenomenon include comfort, hemispheric bias, and attentional factors associated with object proximity. Alternatively, it has been proposed that the degrees of freedom being controlled and the efficiency of that control can also play a role in limb selection (Kim et al., 2007; Stins et al., 2001). Basically, this idea suggests that the selected limb has advantages for more efficient and accurate coordination of limb actions. Stins et al. (2001)



found that the point where participants switched from the dominant to the nondominant arm was associated with the point where deceleration times of both hands were equal. This result implies that limb choice is task-dependent and related to kinematic variables such as deceleration times. It was also found that switching from the dominant right-arm to the non-dominant left-arm reaching in left hemispace reported in earlier work may have emerged from a shift in a shoulder driven reach to an elbow driven reach (Kim et al. 2007). These findings indicate that the selected limb may be systematically related to control efficiency. Based on the idea that a selected limb is the product of control-based movement efficiencies, it is believed that individuals are highly skilled perceivers of their own action capabilities and proficient determiners for a given choice (Stins et al. 2001).

### **Dynamic Dominance Hypothesis**

After many studies have attempted to establish Woodworth's hypothesis as an explanation in limb difference, the two component perspective has generally failed to generalize the characteristics of limb differences in various performances (Sainburg, 2005). As an alternative explanation, one of the most recognized contemporary theories is the DDH (Sainburg & Kalakanis, 2000, Sainburg, 2005), a notion that has generated much discussion and several studies in recent years (e.g., Bagesteiro & Sainburg, 2003; Duff & Sainburg, 2007; Heuer, 2007; Wang & Sainburg, 2007). Basically, the findings associated with this perspective suggest that the dominant (right) arm has advantages in controlling limb segment inertial dynamics. For example, right-arm reaches produce more efficient use of shoulder interactive torque; whereas, left-arm reaches require more active control of elbow torques. In essence, the right-arm shows more efficient coordination by producing

the same movement with less torque. Later work found that during aimed movements, the right arm displayed advantages for coordinating intersegmental dynamics associated with *specifying trajectory speed and direction*, while the left arm revealed advantages in controlling limb impedance; i.e., *final position control* (Duff & Sainburg, 2007). In regard to the latter observation, interestingly, the left arm often achieves more accurate final positioning, regardless of errors in coordination during the movement. These findings have led to the notion that the left arm may be specialized for control of steady state limb position, which emerges only during the final phase of reaching movements (Bagesteiro & Sainburg, 2003).

More specifically, these findings are categorized into three main features. The first main feature of the DDH is ‘lateralization of intersegmental coordination’. In order to control intersegmental coordination of the multiple segments of the limbs, muscle activity patterns must be modulated to counter intersegmental interaction torques. To examine this dynamic interaction mechanism, Sainburg and colleagues manipulated a reaching task that would produce three different shoulder motions and identical elbow motions (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). They found that elbow interaction torque of the dominant arm contributed approximately 50% to elbow net torque, indicating well distributed and coordinated two-joint (elbow and shoulder) motions. On the other hand, elbow interaction torque of the nondominant arm contributed little to elbow net torque, reflecting little shoulder contribution to elbow motion. Thus, the nondominant arm reaches were made mostly by elbow muscle torque, whereas the dominant arm reaches were driven evenly by both elbow and shoulder motions, indicating less muscle torques and greater

interaction torques on the elbow (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). This finding implies that the nondominant limb has less efficient torque control compared to the dominant limb. In addition, electromyographic (EMG) recordings have supported this finding that the dominant arm has better anticipation of planned movements (Bagesteiro & Sainburg, 2002). As a consequence of the anticipation, the dominant arm takes advantage of intersegmental dynamics while executing movements.

The second feature, 'dominant limb advantages are specific to controlling dynamics' is derived from the prediction, "features of control that do not stress intersegmental dynamics should not elicit dominant arm advantages" (p.208) (Sainburg, 2005). In order to examine this hypothesis, they compared two reaching tasks that would result in the same degree of error (large curvature) but different task dynamics in the movements (Sainburg, 2002). In other words, one task was designed to produce novel interaction torque through unexpected inertial load due to eccentric attachment of a forearm brace. The other task reflected a center-out reaching task through a 30 degree visuomotor rotation. Both manipulations showed large curvature at the initial stage. After many adaptative trials, the dominant arm showed more reduced error in the inertial load task than the nondominant arm, whereas both arms revealed similar visuomotor adaptations. Thus, this result supported the fact that the dominant arm is specialized in the control of limb dynamics.

The last feature of the DDH is 'nondominant specialization for control of limb position.' Compared to the dominant arm, the nondominant arm has generally been known as a relatively unskillful and unpracticed system. However, several previous studies of

Sainburg and colleagues have repeatedly shown the finding that the final positions of the nondominant arm were often similar or even more accurate than those of the dominant arm (Bagesteiro & Sainburg, 2002; Bagesteiro & Sainburg, 2003; Sainburg, 2002; Sainburg & Kalakanis, 2000). They interpreted this finding as suggesting that the dominant system may sacrifice final position accuracy for improving intersegmental coordination. In order to investigate the third hypothesis, they employed unexpected inertial load as a perturbation during reaching movements (Bagesteiro & Sainburg, 2003). Participants in this study had to execute 20 degree elbow flexion movements using a single-joint (elbow) reaching task. During reaching movements, a 2-kg object was added to the forearm on random trials without presenting information about the mass to participants. The result of EMG activity revealed that the nondominant arm showed effective load compensation for the perturbation, whereas the dominant arm showed overcompensation for the load. As a result, the dominant arm made a larger error of final position while the nondominant showed no significant differences in final position accuracy between loaded and unloaded trials. These finding support the hypothesis that the nondominant system is specialized in controlling limb position.

In summary, these studies provide evidence that the two arm controllers (right and left) employ different strategies while driving a reaching action. The right arm system stabilizes dynamic features of the desired movement, such as trajectory and segment torques, while the left-arm controller stabilizes end-point impedance for achieving steady state posture. Wang and Sainburg (2007) suggest that "... rather than viewing the right arm as generally 'superior' to the left arm, we suggest that control has become distributed

across the two systems, such that each controller has become adapted for different, but complimentary cost-functions” (p.568).

### **Research Questions**

The research questions for this study were posed to examine the generalization of the DDH in regard to limb dominance, limb selection, and limb action. Arguably, the DDH presents a reasonable explanation of the differences between dominant and nondominant limbs for reaching movements. However, the current generalization of the DDH is somewhat insufficient. This lack of generalization of the DDH was also noted in one of the recent studies from Sainburg’s lab. In this study, they failed to support a nondominant specialization for stabilizing steady-state isometric force (Zhang, Sainburg, Zatsiorsky, & Latash, 2006). Besides the failure, the DDH has not been proven in various circumstances.

First, methodologically, the DDH has not been tested with a task involving a free-choice paradigm (limb selection). That is, the DDH appears to be only relevant in a forced-choice condition. Research indicates that right-handers typically switch from the dominant arm to nondominant arm in limb selection when reaching toward left hemisphere (Gabbard & Helbig, 2004; Helbig & Gabbard, 2004). Also, Stins et al. (2001) found that people know the most efficient or economical action for a specific environment and task, and they can select the best way to move. These suggestions induce research questions: *Can the DDH explain why people select their nondominant hand? Can the nondominant limb advantage for controlling final limb position in the DDH be the determinant of nondominant hand use? If so, is the nondominant advantage in the DDH the only reason why people select their nondominant hand?*

Second, the DDH has not been tested in strongly lateralized left-handers (limb dominance). Thus, this hypothesis has been tested in only strongly lateralized right-handers. There are few studies of the DDH with strong left-handers. To date, only one study was found that tested this idea (Wang & Sainburg, 2007). Personal communication with the lead author revealed that due to the difficulty with finding strong left-handers, the lateral index for the participants was moderate to weak. With the experiments described here, only strongly lateralized left-handers were used. Previous work leads us to assume that interlimb differences between handedness groups may not mirror each other. Although considerable individual variation exists, a common theme found in the literature is the observation that hemispheric asymmetry and cortical representation for a typical group of left-handers is not as large as for a group of right-handers (Sörös, Knecht, Imai, Gürtler, Lütkenhöner, Ringelstein, & Henningsen 1999; Hellige et al., 1994; Iaccno, 1993). However, in spite of the lack of a strong left-handed population, it is still important to attempt to understand differences between strong right- and strong left-handers. Therefore, the second questions are “*Do predictions of the DDH hold for right- and left-handers?*” “*Can the DDH show the same results in strong left-handers as shown in strong right-handers?*”

Finally, we aim to determine if general features of the DDH apply to reaches with a wide range of speed (limb action). People generally perform a similar speed for a given motor task, such as reaching for an object. In the previous studies, the similar range of limb speed was found for reaching movements. That is, reaching movements were performed at the participant’s elected natural speed with an average of 600 ms, with the right and left

hands showing a similar time course (Bagesteiro & Sainburg, 2002; Bagesteiro & Sainburg, 2003; Sainburg, 2002; Sainburg & Kalakanis, 2000). One well-known determinant of movement time is the speed-accuracy trade-off: movement time increases with the accuracy requirement (Woodworth, 1899; Fitts, 1954; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). According to this view, movement slowing seems to be a compensatory response: people slow down because of a loss of accuracy (Sheridan & Flowers, 1990). However, factors other than the speed-accuracy trade-off may influence movement time. One possible determinant is the energetic cost of making a movement (Todorov & Jordan, 2002). Thus this implies that people would not move fast unless there are energetic advantages even though they can move faster than natural speed for a given task. It is our assumption that a change in speed may influence limb selection for reaching. If there is insufficient time to correct or change the direction of movement, does the dominant arm still have an advantage in control compared to the nondominant arm? In other words, if there is sufficient time to execute movements, can the nondominant limb improve joint coordination patterns? Another assumption is that a change of limb speed may alter limb kinetics and kinematics. This assumption implies that movement speed can influence the DDH in terms of the distinct characteristics of each limb. Therefore, the third question for generalization of the DDH was “*Do propositions of DDH apply to reaches with a wide range of speeds (slow and fast)?*”

### **Purpose of the Study**

The primary intent of the present study was to investigate the generalization of the DDH in regard to limb selection phenomenon among strong right- and left-handed

participants. More specifically, the purpose of this study was to explore the following questions.

1. *Can the DDH explain why people select their nondominant hand for reaching into their contralateral hemispace? (Limb selection)*
2. *Do predictions of the DDH hold for right- and left-handers? (Limb dominance)*
3. *Do propositions of the DDH hold for a wide range of speeds? (Limb action)*

To address these questions, the present study was divided into two studies. Study 1 was designed to test generalization of the DDH using a free-choice paradigm (limb selection) and to examine the differences of movement efficiencies between the selected and the assigned actions with both handedness groups (Limb dominance). In Study 2, we further investigated the DDH using slow and fast reaches with both handedness groups in order to determine whether the DDH can be applied to reaching movements with substantially different speed (Limb action). Consequently, the aims of this research were to test the effect of hand (dominant- vs. nondominant-arm), handedness group (right- vs. left-handers), limb selection (free- vs. forced-choice), task complexity (target size and speed), and object positions (50° to 130°) on the kinematics and kinetics of reaching.



## CHAPTER II

### STUDY 1: LIMB SELECTION AND LIMB DOMINANCE

Arguably, the *Dynamic Dominance Hypothesis* (DDH) is one of the most recognized contemporary perspectives in handedness studies. The more traditional view of handedness asserts that the trait is basically an invariant feature characterized by superiority of the dominant limb, which is the right for the vast majority of the population. Indeed, a general review of motor behavior literature indicates that right-handed individuals typically execute aiming movements with better speed, smoothness, consistency and accuracy when performing them with their right hand (Carey, Hargreaves, & Goodale, 1996; Carey, & Otto-de Haart, 2001; Carello, Groszofsky, Reichel, Soloan, & Turvey, 1989; Hellige, & Kee, 1990). However, the DDH focuses on interlimb differences with the general idea that the two arms are differentially specialized for actions (Bagesteiro & Sainburg, 2002; Sainburg, 2002). More specifically, this notion proposes that each hemisphere limb system is specialized for controlling different features of a reaching action more efficiently. In other words, even among strongly lateralized right-handers, the non-dominant left limb is advantageous in specific situations (Bagesteiro & Sainburg, 2002; Sainburg, 2002). The DDH has been abundantly tested in strongly lateralized right-handers (Bagesteiro & Sainburg, 2002, 2003; Duff & Sainburg, 2007; Heuer, 2007; Sainburg, 2002, 2005; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2007). However, the hypothesis has not been tested in strongly lateralized left-handers. There are little studies of the DDH with strong left-handers. A common theme found in the literature is the

observation that hemispheric asymmetry and cortical representation for a typical group of left-handers is not as large as for a group of right-handers (Sörös et al., 1999; Hellige et al., 1994; Iaccno, 1993). However, in spite of the lack of strong left-handed population, it is still worth attempting to understand differences between strong right- and left-handed populations.

Research has shown that regardless of hand preference, the vast majority of individuals switch limbs for simple reaching and grasping based on the proximity of the object. With interest in how the underlying limb kinematics that might reveal control processes for limb choice, we compared strong right-handers on right- and left-arm reaches at nine positions in hemispace. The hypotheses, based on the previous work (Kim et al. 2007) and the work of Stins et al. (2001), focused on limb comparisons regarding reduction in the control of joints and time spent in limb deceleration. Our results indicated that the profiles between the switch in limb selection around  $80^\circ$  ( $90^\circ$  was midline) and switch in deceleration times were similar in left-hemispace, but not in right-hemispace. This outcome suggested that control efficiency with regard to amount of time devoted to feedback processing that might occur in the deceleration phase of the reach did not fully account for limb switching. As a result, we concluded that the limb switching phenomenon was linked to joint amplitudes associated with the freely selected limb, rather than time spent decelerating the limb (Kim et al., 2007). However, this conclusion was somewhat incomplete due to the absence of kinetic (i.e. joint torques) data in the previous study. Even though the kinematic variables were similar for both hands, kinetic analysis might reveal differences in the control strategies employed for the right and left arms. For

example, similar movement times or hand path trajectories did not always indicate similar joint coordination patterns during the movement. Therefore, the intent of the present study was to examine whether the relationship between the switch in limb selection and the DDH can explain limb selection phenomenon and to compare strong right- and left-handers using a free-choice paradigm.

Based on the DDH, we predicted that the dominant arm would show advantages in the control of limb dynamics and the nondominant arm would reveal more accurate final position in both hand groups (strong right- and left-handers). In order to identify the advantages of each arm, nine target positions were divided into new five positions. Each new position consisted of two target positions, which produce anatomically and mechanically homologous movements for both limbs. In limb selection analysis using free-choice and forced-choice paradigms, we predicted that the selected limb would produce shorter movement times and be better accuracy, with more efficient torque than the unselected limb in both handedness groups. Furthermore, we also predicted that the transition point in limb selection between the two hands would correlate with the point where the deceleration times were identical.

## **Method**

### *Participants*

10 right-handed and 10 left-handed adults, ages 19 to 23 years old, participated in Study 1. The participation was limited to strong right- and strong left-handers; that is, only those individuals that used their right or left hand consistently with all four preference tasks as described in the Lateral Preference Inventory (Coren 1993). With regard to the

collection of strong left-handers, a general comment is warranted: one out of ten was a left-hander and three out of those 10 were strong left-handers. The experimental protocol and consent form were approved by the Texas A&M Institutional Review Board (IRB) for the ethical treatment of human subjects. The participants were informed of the experimental procedures and risk level and voluntarily signed a consent form before participating in this study.

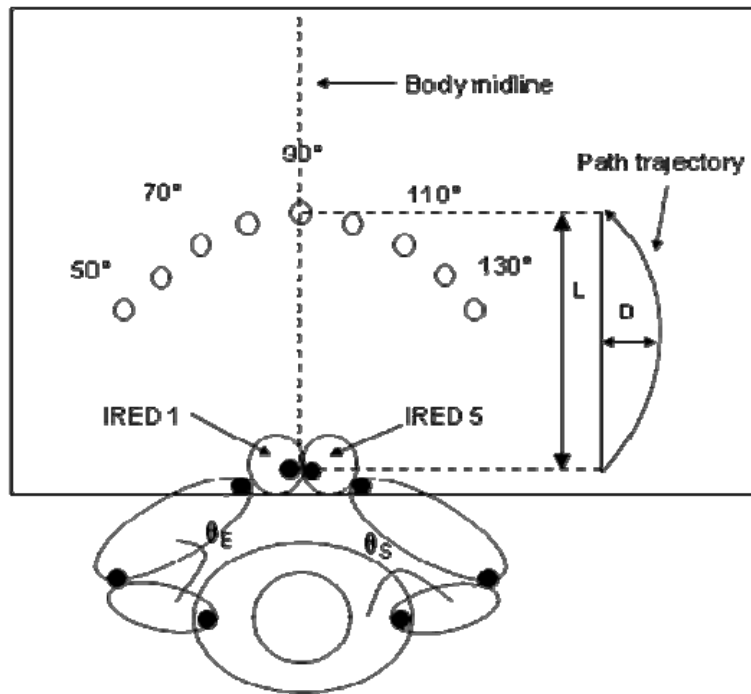
### *Apparatus*

Eight infrared light-emitting diodes (IREDs) were attached to the index finger tip (IREDs 1 & 5), the wrist (IREDs 2 & 6), the elbow (IREDs 3 & 7), and the shoulder (IREDs 4 & 8) of each arm (Fig. 1). The 3D trajectories of the IREDs were recorded with a VICON 460 3D camera system. Equipped with four cameras, the system provided an overall accuracy of  $63 \pm 5 \mu\text{m}$  and overall precision (noise level) of  $15 \mu\text{m}$  for the most favorable parameter setting. Arbitrary changes in camera arrangement revealed variations in mean accuracy between 76 and 129  $\mu\text{m}$ . The noise level normal to the cameras' projection plane was found higher compared to the other coordinate directions (Windolf, Gotzen, & Morlock, 2008). The static and dynamic calibration of the system was performed before each experimental day. The x, y, z values of all IREDs were low-pass filtered at 10 Hz (2<sup>nd</sup> order, dual pass Butterworth). All kinematic and kinetic data analysis was performed using MATLAB 7.0 (Mathworks Inc.).

### *Procedure*

The participants sat in a flat seat (parallel to the floor) with a backrest that was perpendicular to the seat. While seated in an upright position, chair height was adjusted

until the position of arms was parallel to the table. Each trial began with the participant's arms positioned in hand rests on the middle area of the body. All targets were presented at 75% of maximum arm length (semi-circular positioning) and presented randomly by a beam projector mounted on the ceiling at nine different positions; the body midline (labeled 90°), 80°, 70°, 60° and 50° to the left of midline, and 100°, 110°, 120°, 130° to the right of the body midline (Fig. 1). The size of targets consisted of big (3 cm in diameter) and small (1 cm in diameter) targets. Without any auditory or visual starting cue, participants were instructed to perform a reach and hit the target as quickly and accurately as possible after one of nine targets appeared. In each trial, participants had to select one hand (free-choice). After one free-choice reach, participants were instructed to execute another reach to the same target with the opposite hand (forced-choice) in order to compare the performance of both arms. Each participant produced three reaches with each hand for each object and each target size for a total of 108 trials. Testing for each participant was completed in an isolated room and each condition was counterbalanced.



**Figure 1.** View of the experimental set-up for Study 1. Acronyms indicate following: L-straight distance from start to end point, D-maximum path deviation,  $\theta_E$ -elbow angle,  $\theta_S$ -shoulder angle.

### *Kinematic Data*

IREDs 1 and 5 were differentiated to yield tangential velocity and acceleration values. Peak tangential velocity was located in each trial and the first point to exceed 5% of peak velocity in the trial was labeled as movement onset, and the first point to drop below 5% of peak velocity before the grasp was labeled as movement termination (Bagesteiro & Sainburg, 2002; Sainburg, 2002). Movement time (MT) was defined as the time between movement onset and movement termination. Acceleration time (AT) was defined as the time from movement onset to peak velocity. Deceleration time (DT) was defined as the time from peak velocity to movement termination. A percentage of the time

spent decelerating the limb (%DT) was calculated as the proportion of DT to MT. The relationship between path linearity and contributing degrees of freedom was investigated by computing elbow and shoulder joint amplitudes. The elbow angle amplitudes (EA) were calculated with IRED 2, 3, and 4 (left-arm), and IRED 6, 7, and 8 (right-arm). The shoulder angle amplitudes (SA) were defined with IREDs 3 and 4 (left-arm), and 7 and 8 (right-arm), and a fixed reference point on the opposite shoulder. For each trial, the maximum angular displacement for the elbow and shoulder angles was determined.

Two measures of movement accuracy were calculated from hand-path curvatures: final position error and hand-path deviation from linearity. Final position error (PE) was calculated as the distance between index finger location at movement end and the target position. A measure of deviation from linearity (DL) was based on IREDs 1 & 5 on the index finger tips and was computed as the ratio of maximum path deviation to the length of a straight line connecting a hand's initial position and the object's position (Bagesteiro & Sainburg, 2002; Sainburg, 2002). A value of PL = 0 indicates a straight path while a value of PL > 0 indicates a deviation from a straight path.

### *Kinetic Data*

Joint torques were calculated for shoulder and elbow using equations detailed in the next page. For the purpose of this study, it was assumed that the upper arm and forearm were two interconnected rigid links with frictionless joints at the shoulder and elbow. In order to separately examine the effect of interactive forces and muscle forces on the limb motion, joint torques at each joint consisted of three main components: interaction torque (IT), muscle torque (MuT), and net torque (NT) (Bagesteiro & Sainburg, 2002; Sainburg,

2002). At each joint,  $IT$  represents the rotational effect of the forces due to the rotational and linear motion of the other segment.  $MuT$  represents the rotational effect of muscle forces acting on the segment.  $NT$  is directly proportional to joint acceleration, inversely proportional to limb inertia, and equal to the combined  $IT$  and  $MuT$  (Sainburg & Kalakanis, 2000; Zajac & Gordon, 1989). It is important to note that computed muscle joint torque cannot be considered a simple proxy for the neural activation of the muscles acting at the joint. Muscle joint torque does not distinguish muscle forces that counter one another during co-contraction and it also includes the passive effects of soft tissue deformation.

#### *Elbow Joint Torques*

$$ITe = -\underline{\Theta}_S * [A * \cos(\Theta_E) + B] - \underline{\Theta}_S^2 * A * \sin(\Theta_E)$$

$$NTe = \underline{\Theta}_E * B$$

$$MuTe = NTe - ITe$$

#### *Shoulder Joint Torques*

$$ITs = \underline{\Theta}_E * A * \cos(\Theta_E) + (\underline{\Theta}_E + \underline{\Theta}_S)^2 * A * \sin(\Theta_E)$$

$$NTs = \underline{\Theta}_S * [C + A * \cos(\Theta_E)]$$

$$MuTs = NTs - ITs + MuTe$$

#### *Symbols*

$$A = m_2 L_1 r_2 + m_d L_d r_d$$

$$B = I_2 + m_2 r_2^2 + I_d + m_d r_d^2$$

$$C = I_1 + m_1 r_1^2 + (m_2 + m_d) L_1^2$$



where  $\Theta_S$  is shoulder angle,  $\dot{\Theta}_S$  is shoulder angle velocity,  $\ddot{\Theta}_S$  is shoulder angle acceleration,  $\Theta_E$  is elbow angle,  $\dot{\Theta}_E$  is elbow angle velocity,  $\ddot{\Theta}_E$  is elbow angle acceleration,  $m$  is mass,  $r$  is distance to center of mass from proximal joint,  $L$  is length, and  $I$  is inertia. The subscripts are defined as follows: 1 is upper arm segment, and 2 is forearm/hand segment. Limb segment inertia, center of mass, and mass were computed from regression equations using the subject's body weight and measured limb segment lengths (Winter, 1990).

### *Statistical Analysis*

In order to analyze limb selection patterns, we used three-way ANOVAs for the percentage of the freely selected right-arm use as a function of 9 Position (50° to 130°), 2 Handedness (right- vs. left-handers), and 2 Target Size (small vs. big). We also performed four-way ANOVAs for each kinematic variable as a function of 2 Selection (free- vs. forced-arm), 9 Position (50° to 130°), 2 Handedness (right- vs. left-handers), and 2 Target Size (small vs. big). Furthermore, in order to identify the DDH and to examine limb difference in reaching movements, target positions were divided into five new positions: *Farthest* (50° and 130°), *Far* (60° and 120°), *Near* (70° and 110°), *Nearest* (80° and 100°), and *Middle* (90°). Reaching movements toward two target positions in each new position were anatomically and mechanically homologous movements for comparison of the dominant-arm with the nondominant-arm. Reaches toward the same side were considered *ipsilateral movements* and reaches toward the opposite side were considered *contralateral movements*. Based on these new positions, we performed separate four-way ANOVAs for final position accuracy and kinetic variables as a function of 2 Hand (dominant- vs.

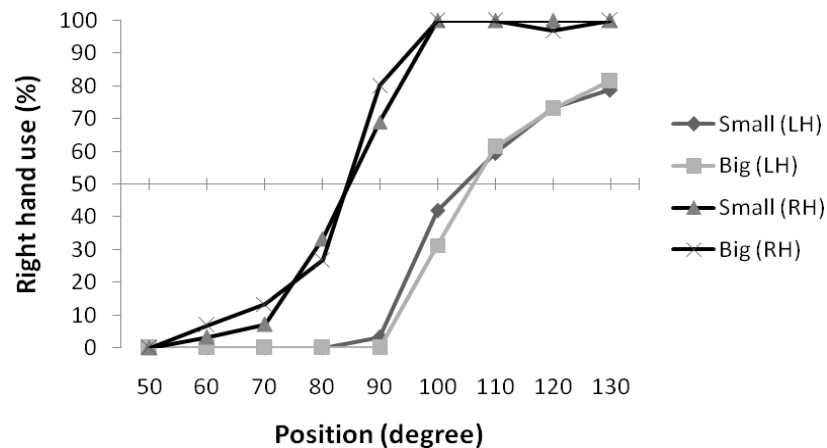
nondominant-arm), 5 Position (farthest to middle), 2 Handedness (right- vs. left-handers), and 2 Target Size (small vs. big). Bonferroni/Dunn post hoc analyses were also used to test for any significant interaction effects. The significance level for all main effects and interaction effects was set at  $p < .05$ .

## **Results**

### *Limb Selection*

The percentage of free-choice reaches executed with the right hand as a function of Position ( $50^\circ$  to  $130^\circ$ ), Size (small vs. big), and Handedness (right- vs. left-handers) is illustrated in Figure 2. The ANOVA for the percentage of reaches revealed main effects for Handedness,  $F(1, 32) = 12.3, p < .01$ , and Position,  $F(8, 32) = 9.3, p < .01$ . Also, we found a Handedness  $\times$  Position interaction,  $F(8, 32) = 53.1, p < .01$  and no other main effects or interaction effects were found. Simple main effect analyses for the interaction revealed that right-handers showed significantly greater right-arm use than left-handers for position  $70^\circ$  to  $130^\circ$ . For right-handers, a similar profile was found in the percentage of the free choice with the right hand between the small and big target conditions, right-handed participants showed the switchover point from free right-arm to free left-arm reaches between the object position  $80^\circ$  and  $90^\circ$ . Free left-arm reaches dominated at position  $50^\circ$  to  $80^\circ$  in left hemi-space, and free right-arm reaches dominated at position  $90^\circ$ , and from position  $100^\circ$  to  $130^\circ$  in right hemi-space. On the other hand, left-handed participants showed the switchover point from free right-arm to free left-arm reaches between the object positions  $100^\circ$  and  $110^\circ$ . Free left-arm reaches dominated at position  $90^\circ$  and from  $80^\circ$  to  $50^\circ$  in left hemi-space and position  $100^\circ$  in right-hemisphere. Free right-arm reaches dominated at

positions 120° and 130° in right hemi-space. Also, for left-handers, a similar profile was found in the percentage of the free choice with the right hand between the small and big target conditions. Thus, these results indicated that target size conditions did not influence limb selection, whereas handedness changed the switchover point from 80° (right-handers) to 100° (left-handers) in limb selection.

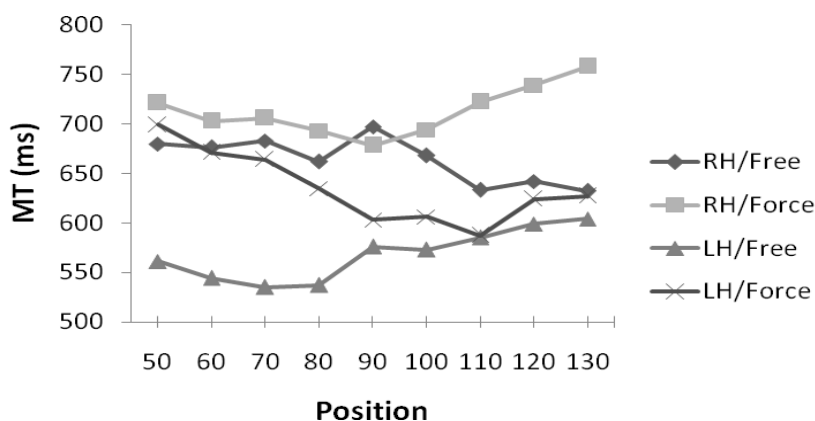


**Figure 2.** Percentage of reaches executed with the right arm for Study 1. The point on the abscissa corresponding to where the 50% line crosses the curve for each condition marks the point at where both hands may have been used equally often (e.g. 85° and 105°).

### *Limb Kinematics*

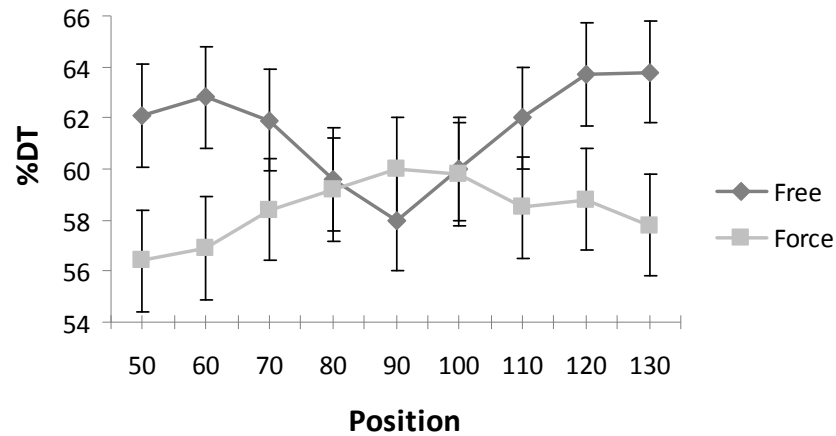
*Movement time (MT).* The ANOVA for MT revealed main effects for Handedness,  $F(1, 2097) = 301, p < .01$ , Position,  $F(8, 2097) = 2.3, p < .05$ , Target Size,  $F(1, 2097) = 571.6, p < .01$ , and Selection,  $F(1, 2097) = 135.7, p < .01$ . Thus, left-handers (600 ms) had shorter MTs than right-handers (687 ms) with the big target condition (583 ms) having

shorter MTs than the small target condition (702 ms). Regardless of position, target size, and handedness, the freely selected arm (614 ms) had shorter MTs than the forced arm (672 ms). More specifically, simple main effect analyses for the Size  $\times$  Selection interaction  $F(1, 2097) = 10.4, p < .01$ , revealed that the free-arm (682 ms) had shorter MT than the forced-arm (723 ms) when reaching for the small target and that the free-arm (546 ms) had shorter MTs than the forced-arm (622 ms) for the big target. Also, simple main effect analyses for the Position  $\times$  Handedness  $\times$  Selection interaction,  $F(8, 2097) = 7.8, p < .01$ , revealed that for right-handers the free-arm was significantly faster than the forced-arm for positions 110° to 130°, whereas for left-handers the free-arm was significantly faster than the forced-arm for positions 50° to 80° (Fig. 3).



**Figure 3.** Movement times (MT) plotted as a function of Position, Handedness, and Selection for Study 1.

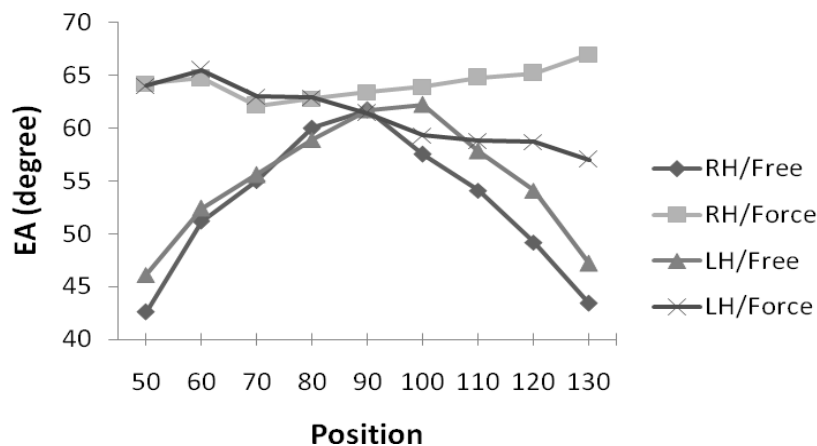
*Deceleration time (%DT)*. The ANOVA for %DT revealed main effects for Handedness,  $F(1, 2097) = 537, p < .01$ , Size,  $F(1, 2097) = 292, p < .01$ , and Selection,  $F(1, 2097) = 79.2, p < .01$ . Thus, these results indicated that right-handers (64%) spent more time decelerating the arm than left-handers (55%) with a larger proportion of MT devoted to deceleration in the small target condition (63%) compared to the big target condition (56%). Regardless of position, target size, and handedness, the freely selected arm (61%) spent more time decelerating than the forced arm (58%). Also, we found a Handedness  $\times$  Size interaction,  $F(1, 2097) = 4.9, p < .05$ . Simple main effect analyses for the Handedness  $\times$  Size interaction revealed that left-handers spent less time decelerating the arm than right-handers when reaching for the small target (59 vs. 67 %, respectively) and for the big target (52 vs. 61 %, respectively). Also, simple main effect analyses for the Handedness  $\times$  Selection interaction,  $F(1, 2097) = 31.7, p < .01$ , revealed that for right-handers the forced-arm spent less time decelerating than the free-arm (61 vs. 66 %, respectively) while for left-handers the forced-arm spent slightly less time decelerating than the free-arm (55 vs. 56 %, respectively). Another simple main effect analyses for the Position  $\times$  Selection interaction,  $F(8, 2097) = 7, p < .01$ , revealed that the free-arm spent more time decelerating than the forced-arm for positions 50° to 70°, and for positions 110° to 130° (Fig. 4)



**Figure 4.** Percentages of deceleration times (%DT) plotted as a function of Position and Selection for Study 1.

*Joint angles (EA and SA).* We found significant main and interaction effects for EA and SA as a function of Position, Handedness, Size, and Selection. First, the ANOVA for EA revealed a main effect for Position,  $F(8, 2097) = 42, p < .01$ , and interactions for Position  $\times$  Handedness,  $F(8, 2097) = 2.5, p < .05$ , Position  $\times$  Selection,  $F(8, 2097) = 52.8, p < .01$ , and a three-way of Position  $\times$  Handedness  $\times$  Selection,  $F(8, 2097) = 10.5, p < .01$  (Fig. 5). Simple main effect analyses for the interaction revealed that for right-handers the free-arm (mostly left) had smaller EA than the forced-arm (mostly right) for positions 50° to 70°, and the free-arm (mostly right) had smaller EA than the forced-arm (mostly left) for positions 100° to 130°. For left-handers, the free left-arm had significantly smaller EA than the forced right-arm for positions 50° to 80°, and the free-arm (mostly right) had smaller EA than the forced-arm (mostly left) for positions 120° and 130° (Fig. 5). Also, we found a main effect for Selection,  $F(1, 2097) = 787, p < .01$ , and a Handedness  $\times$  Selection

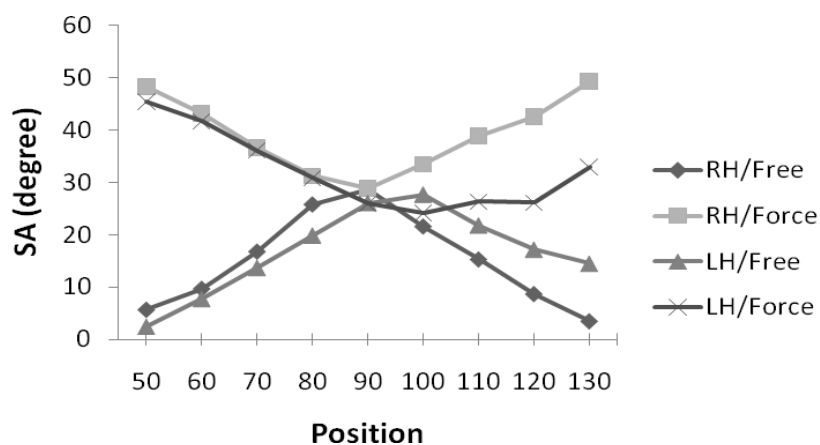
interaction,  $F(1, 2097) = 80.8, p < .01$ . Simple main effect analyses for the Handedness  $\times$  Selection interaction revealed that the free-arm showed significantly less EA than the forced-arm for both right-handers and left-handers.



**Figure 5.** Elbow angle amplitudes (EA) plotted as a function of Position, Handedness, and Selection for Study 1.

The ANOVA for SA revealed main effects for Position,  $F(8, 2097) = 3.5, p < .01$ , Handedness,  $F(1, 2097) = 44.9, p < .01$ , and Selection,  $F(1, 2097) = 2484, p < .01$ . Also, we found interactions for Position  $\times$  Selection,  $F(8, 2097) = 147.4, p < .01$ , and Handedness  $\times$  Selection,  $F(1, 2097) = 118.9, p < .01$ . Simple main effect analyses for the Handedness  $\times$  Selection interaction revealed that the free-arm had smaller SA than the forced-arm for both right-handers ( $15^\circ$  vs.  $39^\circ$ , respectively) and left-handers ( $16^\circ$  vs.  $32^\circ$ , respectively). Simple main effect analyses for the Position  $\times$  Handedness  $\times$  Selection

interaction,  $F(8, 2097) = 28.3, p < .01$ , revealed that for right-handers the free-arm (mostly left) had smaller SA than the forced-arm (mostly right) for positions  $50^\circ$  to  $70^\circ$ , and the free-arm (mostly right) had smaller SA than the forced-arm (mostly left) for positions  $100^\circ$  to  $130^\circ$ . On the other hand, for left-handers the free-arm (mostly left) had significantly smaller SA than the forced-arm (mostly right) for positions  $50^\circ$  to  $80^\circ$ , and the free-arm (mostly right) had smaller SA than the forced-arm (mostly left) for positions  $110^\circ$  to  $130^\circ$  (Fig. 6).



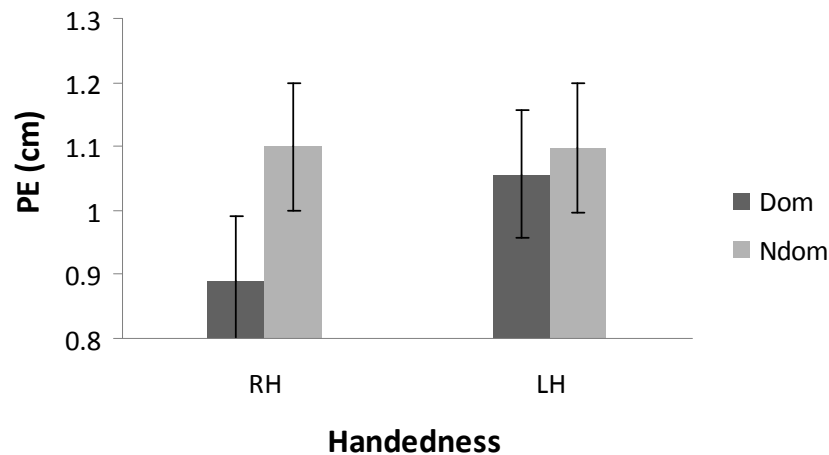
**Figure 6.** Shoulder angle amplitudes (SA) plotted as a function of Position, Handedness, and Selection for Study 1.

#### *Movement Accuracy*

*Final position error (PE).* In order to identify movement accuracy advantage for the nondominant arm as indicated in the DDH, we performed separate four-way ANOVAs (ipsilateral and contralateral) for PE and DL as a function of 5 Position (Farthest: 50 and

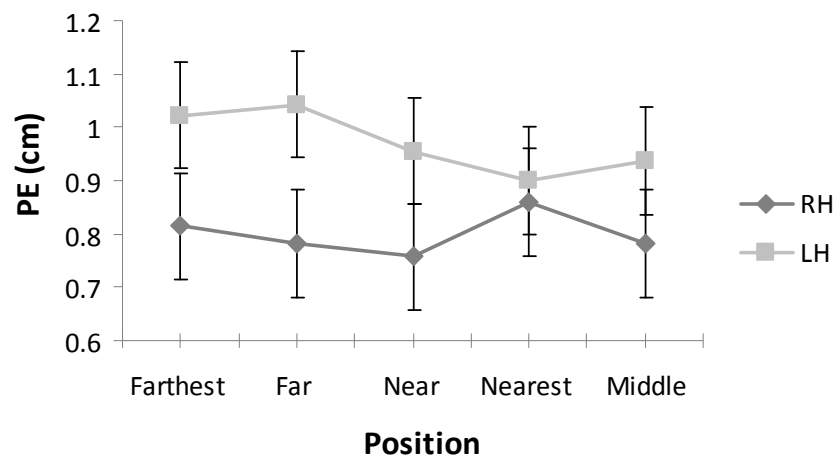


130°, Far: 60 and 120°, Near: 70 and 110°, Nearest: 80 and 100°, Middle: 90°), 2 Handedness (right- vs. left-handers), 2 Size (small vs. big), and 2 Hand (dominant vs. nondominant). For ipsilateral movements, first of all, the ANOVA for PE revealed a main effect for Size,  $F(1, 1197) = 9, p < .01$ . Thus, regardless of position, hand, and handedness, the small target (0.97 cm) revealed less PE than the big target (1.09 cm). We also found main effects for Position,  $F(4, 1197) = 12.1, p < .01$ , Handedness,  $F(1, 1197) = 4, p < .05$ , and Hand,  $F(1, 1197) = 10.5, p < .01$ , and an interaction for Handedness  $\times$  Hand,  $F(1, 1197) = 4.6, p < .05$ . Simple main effect analyses for the interaction revealed for right-handers that the dominant-arm (0.89 cm) was significantly more accurate than the nondominant-arm (1.1 cm), whereas for left-handers the dominant-arm (1.05 cm) and the nondominant-arm (1.09 cm) showed similar final-position accuracies and revealed no statistical difference (Fig. 7).



**Figure 7.** Final position error (PE) for ipsilateral movements plotted as a function of Handedness and Hand for Study 1.

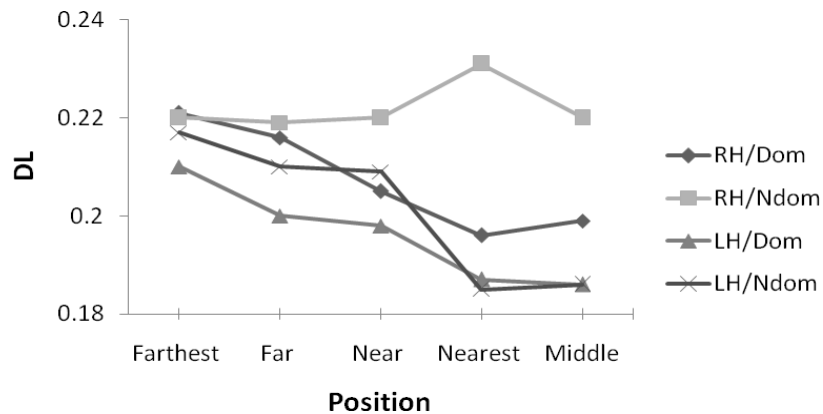
For contralateral movements, the ANOVA for PE revealed a main effect for Size,  $F(1, 1139) = 26, p < .01$ . Thus, regardless of position, hand, and handedness, PE associated with the small target (0.8 cm) was less than PE associated with the big target (0.97 cm). We also found a main effect for Handedness,  $F(1, 1139) = 21.7, p < .01$ , and an interaction for Handedness  $\times$  Position,  $F(4, 1139) = 2.5, p < .05$ . Simple main effect analyses for the interaction revealed right-handers had more accurate final position than left-handers for four of five positions (Fig. 8).



**Figure 8.** Final position error (PE) for contralateral movements plotted as a function of Handedness and Position for Study 1.

*Deviation from linearity (DL).* For ipsilateral movements the ANOVA for DL revealed main effects for Handedness,  $F(1, 1197) = 41.2, p < .01$ , Hand,  $F(1, 1197) = 19.3, p < .01$ , and Size,  $F(1, 1197) = 6.4, p < .05$ . We found an interaction for Position  $\times$  Handedness,  $F(4, 1197) = 5.6, p < .01$ , and a three-way interaction for Position  $\times$  Handedness  $\times$  Hand,

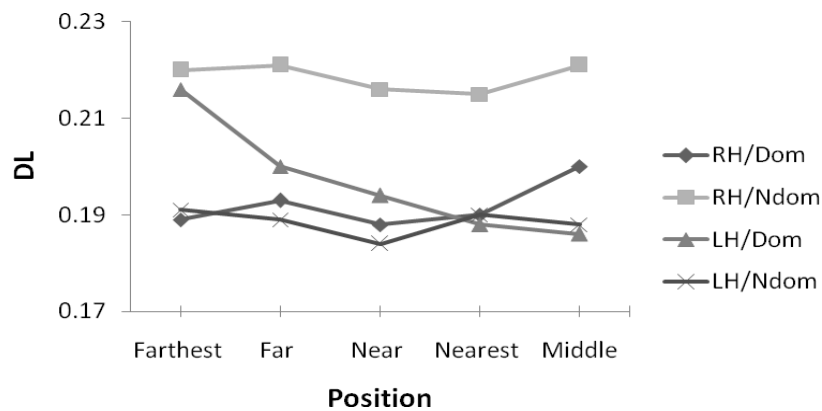
$F(4, 1197) = 5.6, p < .01$ . Simple main effect analyses for the three-way interaction revealed that for right-handers the dominant-arm had straighter hand-path than the nondominant-arm for the Nearest and Middle positions. On the other hand, for left-handers there were no differences in hand-path straightness between the dominant- and nondominant-arm for all positions (Fig. 9).



**Figure 9.** Deviation from linearity (DL) for ipsilateral movements plotted as a function of Position, Handedness and Hand for Study 1.

For contralateral movements, the ANOVA for DL revealed main effects for Handedness,  $F(1, 1139) = 27.1, p < .01$ , Hand,  $F(1, 1139) = 18.8, p < .01$ , and Size,  $F(1, 1139) = 5.3, p < .05$ . We found interactions for Position  $\times$  Handedness,  $F(4, 1139) = 2.4, p < .05$ , and Handedness  $\times$  Hand,  $F(1, 1139) = 53.8, p < .01$ , and a three-way interaction for Position  $\times$  Handedness  $\times$  Hand,  $F(4, 1139) = 2.6, p < .05$ . Simple main effect analyses for the interaction revealed that for right-handers the dominant-arm had a straighter hand-path

than the nondominant-arm for all positions (Fig. 10). On the other hand, for left-handers the nondominant-arm had straighter hand-path than the dominant-arm only for the Farthest position and the difference in hand-path straightness increased as target was moved away from the body midline (Fig. 10).



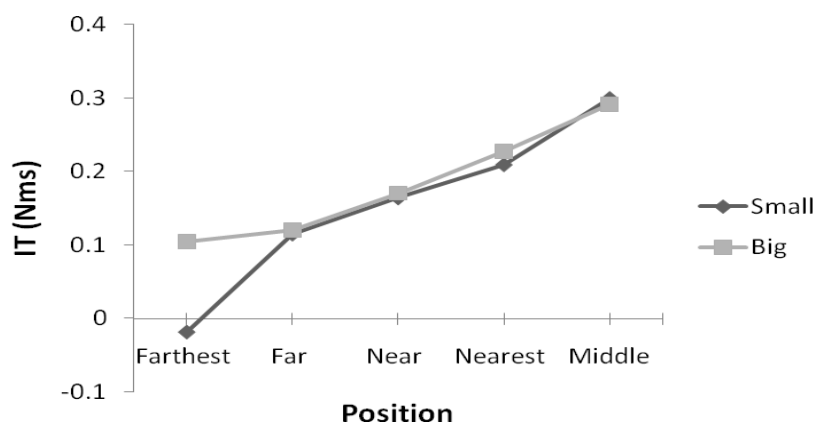
**Figure 10.** Deviation from linearity (DL) for contralateral movements plotted as a function of Position, Handedness and Hand for Study 1.

### *Limb Kinetics*

In order to obtain torque impulses, original shoulder and elbow torques derived from the equations (see METHODS) were integrated from movement onset to movement offset. Net joint torque was equal to the summed positive and negative bar plot height. We performed separate four-way ANOVAs (ipsilateral and contralateral) for IT, MuTe, and MuTs as a function of 5 Position (Farthest: 50 and 130°, Far: 60 and 120°, Near: 70 and 110°, Nearest: 80 and 100°, Middle: 90°), 2 Handedness (right- vs. left-handers), 2 Size

(small vs. big), and 2 Hand (dominant vs. nondominant), in order to identify torque advantages for the dominant arm as indicated in the DDH.

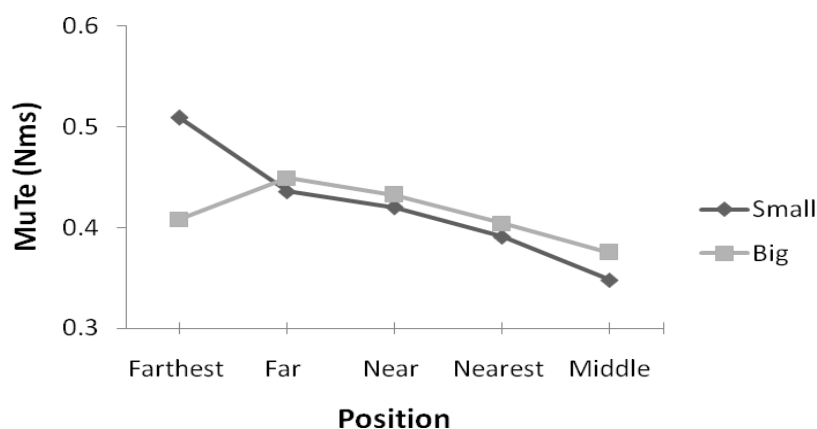
For ipsilateral movements, first of all, the ANOVA for IT revealed that left-handers (0.13 Nms) had less IT than right-handers,  $F(1, 1197) = 39.5, p < .01$ , regardless of position, target size, and hand. Also we found main effects for Position,  $F(4, 1197) = 61.1, p < .01$ , and Size,  $F(1, 1197) = 7.2, p < .01$ , and an interaction for Position  $\times$  Size,  $F(4, 1197) = 4.9, p < .01$ . Simple main effect analyses for the interaction revealed that the small target (-0.01 Nms) had less IT than the big target (0.1 Nms) for the Farthest position (Fig. 11).



**Figure 11.** Interaction torque impulses (IT) for ipsilateral movements plotted as a function of Position and Size for Study 1.

For MuTe, the ANOVA revealed a main effect for Position,  $F(4, 1197) = 6.9, p < .01$ , and an interaction for Position  $\times$  Size,  $F(4, 1197) = 6.9, p < .01$ . Simple main effect

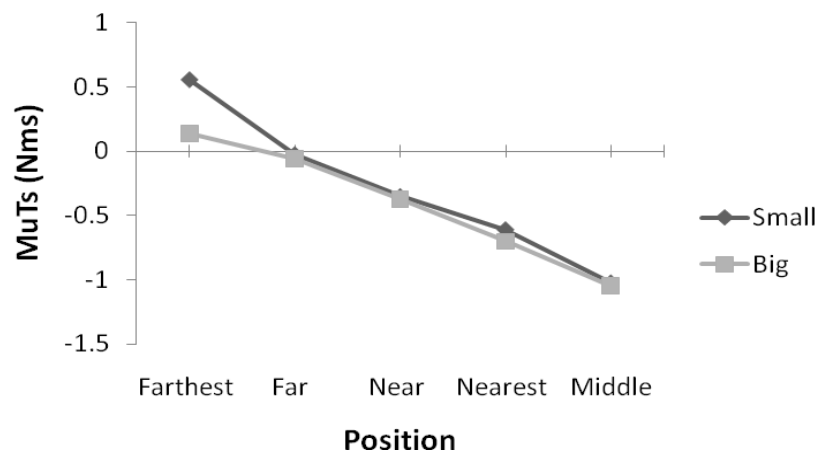
analyses for the interaction revealed that the small target (0.5 Nms) had greater MuTe than the big target (0.4 Nms) for the Farthest positions (Fig. 12).



**Figure 12.** Muscle torque impulses of the elbow (MuTe) for ipsilateral movements plotted as a function of Position and Size for Study 1.

For MuTs, we found a main effect for Handedness,  $F(1, 1197) = 20.1, p < .01$ , and an interaction for Position  $\times$  Size,  $F(4, 1197) = 5.2, p < .01$ . Thus, right-handers (0.43 Nms) had greater MuTs than left-handers (0.27 Nms) and simple main effect analyses for the interaction revealed that the small target (0.5 Nms) had greater MuTs than the big target (0.1 Nms) for the Farthest position (Fig. 13). Overall, for ipsilateral movements, we did not find a main effect of Hand for IT, MuTe and MuTs,  $p > .05$ , and these results indicated that there was no torque advantage of the dominant-arm for both handedness groups. Also, our torque profiles suggested that interaction torques and shoulder muscle torques decreased as target position moved away from the body midline, whereas elbow

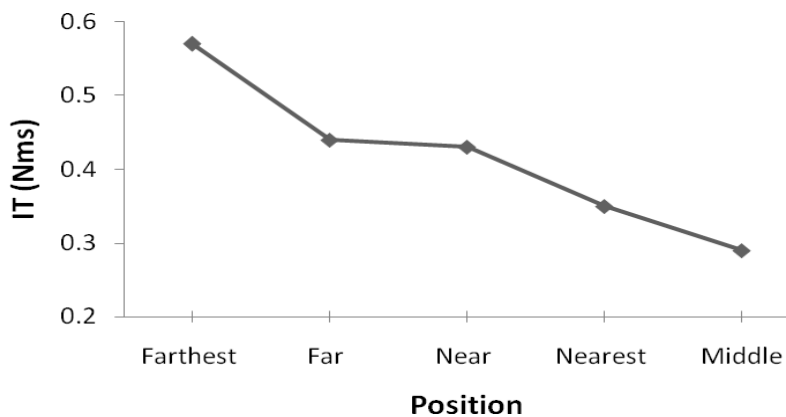
muscle torques increased as target position moved away from the body midline. These results indicated that a reduction in the control of the reach from a two-joint (shoulder and elbow) to a single-joint (elbow) movement occurred as target position moved away from the body midline. Also, our torque profiles revealed that reaches toward the Far position were purely elbow driven action and reaches toward the Farthest position seemed to be the extension of shoulder joint in addition to the extension of elbow joint.



**Figure 13.** Muscle torque impulses of the shoulder (MuTs) for ipsilateral movements plotted as a function of Position and Size for Study 1.

For contralateral movements, the ANOVA for IT revealed that left-handers (0.38 Nms) had less IT than right-handers (0.44 Nms),  $F(1, 1139) = 6.2, p < .05$ , regardless of position, hand, and target size. Also, we found a main effect for Position,  $F(4, 1139) =$

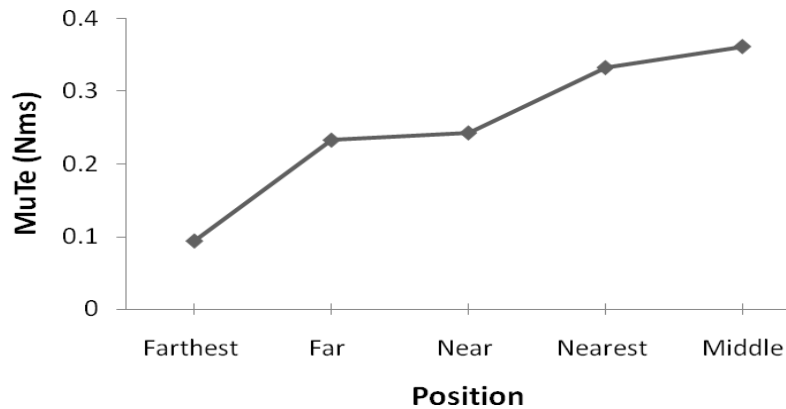
19.7,  $p < .01$ . Post-hoc analysis for the Position effect revealed that all positions were significantly different from each other except the Far and Near positions (Fig. 14).



**Figure 14.** Interaction torque impulses (IT) for contralateral movements plotted as a function of Position for Study 1.

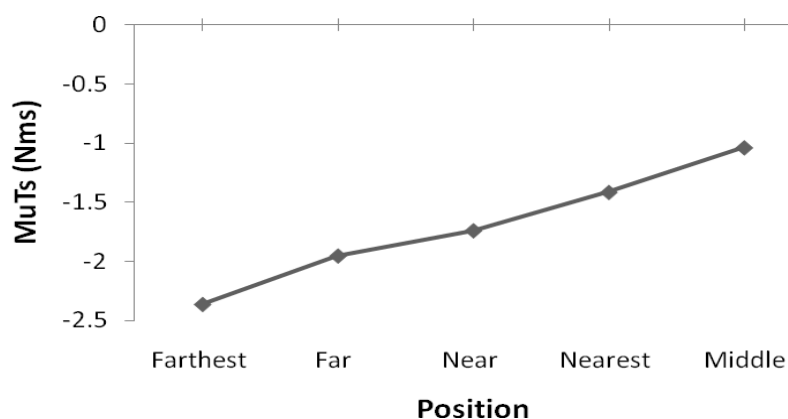
The ANOVA for MuTe revealed main effects for Handedness,  $F(1, 1139) = 11.1$ ,  $p < .01$ , and Position,  $F(4, 1139) = 21$ ,  $p < .01$ . Thus, right-handers (0.28 Nms) had greater MuTs than left-handers (0.21 Nms). Post-hoc analysis for the Position effect revealed that all positions were significantly different from each other except the Far and Near positions (Fig. 15).





**Figure 15.** Muscle torque impulses of the elbow (MuTe) for contralateral movements plotted as a function of Position for Study 1.

For MuTs, we found main effects for Position,  $F(4, 1139) = 110, p < .01$ , and Handedness,  $F(1, 1139) = 15, p < .01$ . Thus, right-handers (-1.77 Nms) showed greater MuTs than left-handers (-1.59 Nms). Post-hoc analysis for the Position effect revealed that all positions were significantly different from each other (Fig. 16). Overall, for contralateral movements, we did not find a main effect of Hand for IT, MuTe and MuTs,  $p > .05$ , and these results indicated that there was no torque advantage of the dominant-arm for both handedness groups. As expected, contralateral reaching revealed that interaction torques and shoulder muscle torques increased as target position moved away from the body midline, whereas elbow muscle torques decreased as target position moved away from the body midline. These findings indicated an increment in a shoulder driven action as target position moved away from the body midline.



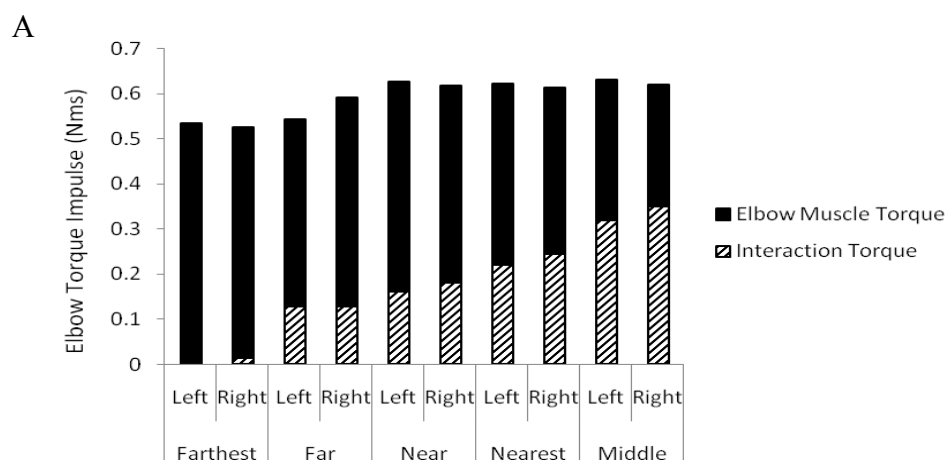
**Figure 16.** Muscle torque impulses of the shoulder (MuTs) for contralateral movements plotted as a function of Position for Study 1.

Interlimb differences in torque contributions illustrated by the stacked bar plots for are shown in Fig. 17; measured as separate contributions to NTe and NTs. The contribution to NTe consisted of MuTe and IT and the contribution to NTs consisted of MuTe in addition to MuTs and IT. In order to obtain torque impulses, original shoulder and elbow torques derived from the equations were integrated from movement onset to movement offset. Net joint torque was equal to the summed positive and negative bar plot height.

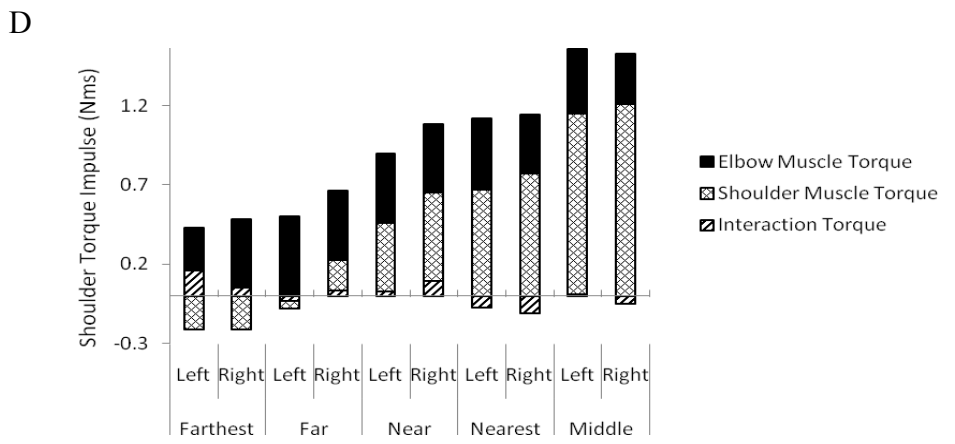
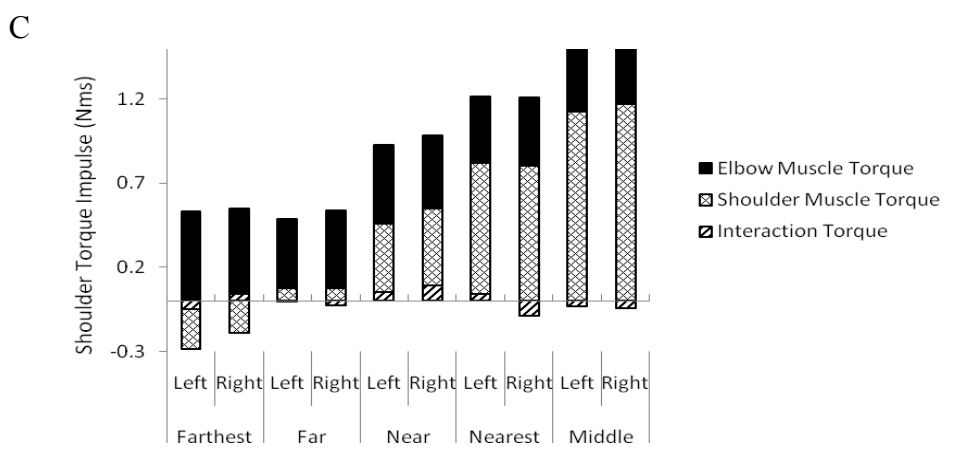
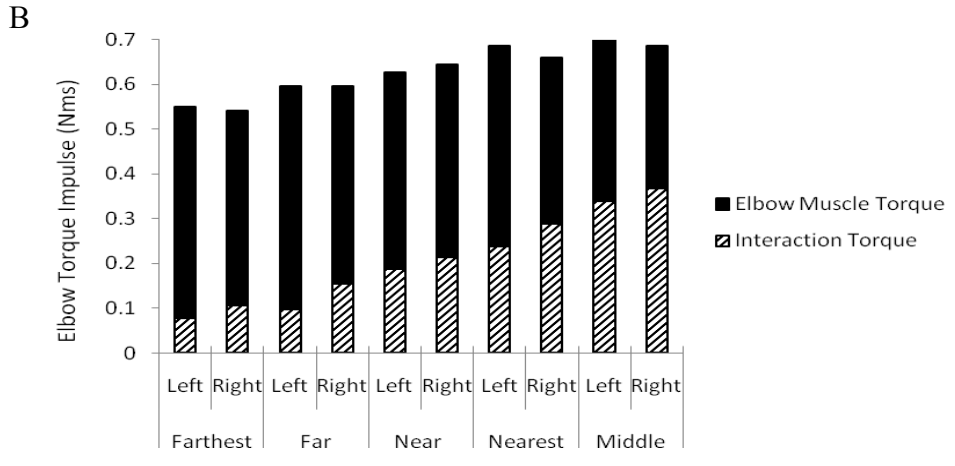
In general, similar torque impulse profiles of big and small target sizes indicated that target sizes did not have influence on elbow and shoulder joint torques except IT. However, variations of NTe and NTs as a function of target position were systematically different. That is, NTe did not vary across target positions and did not show a difference between hands, whereas NTs impulse varied across target positions. Thus, NTs decreased substantially as target position moved away from the body midline (90°). On the other

hand, the contributions of MuTe to NTe increased substantially as target position moved away from the body midline. Along with it, the contribution of IT decreased as a result of an increment in MuTe. However, there was no substantial variation in MuTe among shoulder joint torques. Thus, an increase in MuTs was the primary cause for an increase in NTs.

Regardless of target positions, the contribution of MuTe to NTe was a little smaller for right arm movements as compared to left-arm movements, but not significant,  $p > .05$ . In other words, these data indicated that the contribution of MuTe and IT to net torque impulse revealed no significant difference between the dominant and nondominant arm. On the contrary to propositions of the DDH, our data showed that MuTe did not contribute essentially less toward right elbow movements.



**Figure 17.** Muscle and interaction torque impulses, measured as a contribution to net torque plotted for the elbow joint (A: small target, B: big target) and for the shoulder joint (C: small target, D: big target) for Study 1.



**Figure 17.** Continued

## **Discussion**

The primary intent of the present study was to investigate generalization of the DDH suggested by Sainburg and his colleagues in regard to kinematics and kinetics as a function of handedness, target position, hand, and task complexity (target size). Specifically, this study addressed the following questions: *Can the DDH explain why people continue to select their dominant hand when reaching into their contralateral hemispace? Do predictions of the DDH hold for right- and left-handers?* Therefore, the study examined limb difference employed for right and left arms during reaching movements made by right-handed and left-handed participants. Reaching movements were made to each of nine targets using free-choice and forced-choice paradigms.

### *Limb Selection*

With limb selection analysis using free-choice and forced-choice paradigms, we predicted that the freely selected arm would show kinematic advantages over the forced arm for both handedness groups. Furthermore, we also predicted that the transition point in limb selection between limbs would correlate with the point where certain kinematic and kinetic variables were identical as suggested by Stins et al. (2001). For limb selection, we found that the target size condition did not influence limb selection preference for either the right-handed or left-handed participants. The right-handed participants produced 30% free right-arm and 70% free left-arm reaches to target position 80°. Thus, free left-arm reaches dominated at positions 50° to 80° in left hemi-space, and free right-arm reaches dominated from position 90° to 130° in right hemi-space. The left-handed participants performed a similar selection pattern as the right-handed participants, with 40% free right-

arm and 60% free left-arm reaches occurring at position 100°. These findings indicated that a strong tendency to use the dominant arm when reaching to positions close to the midline (Gabbard et al., 2001; Gabbard & Helbig, 2004; Helbig & Gabbard, 2004). However, our results are somewhat different from previous studies. Many studies have attempted to address this issue by investigating tasks of different complexity and to conclude that task complexity is able to alter the transition point in limb selection (Bryden, Pryde, & Roy, 2000; Steenhuis & Bryden, 1989). Generally, as higher task complexity (i.e. our small target) is presented, it is expected to require a larger area of workspace covered by the dominant arm but some findings including our data are inconsistent (Guiard, 1987, 1990). One possibility for the inconsistency between our data and previous data is that our small target size might be not difficult enough compared to our big target size.

As one of our attempts to identify a determinant for the bias, we examined forced-arm reaches (no free-choice) for the right- and left-arm among right-handed participants and found that the degrees of freedom being controlled and the efficiency of that control can also play a role in limb selection (Kim et al., 2007). In other words, switching from dominant right-arm to non-dominant left-arm reaching in left-hemisphere reported in our earlier work may have emerged from a shift in a shoulder driven reach to an elbow driven action (Kim et al. 2007). Also, Stins et al. (2001) found that the point where participants switched from dominant to nondominant arm was associated significantly with the point where the deceleration times of both hands were equal. These findings imply that limb choice is associated with efficiency of limb kinematics. In a recent study (Kim et al, submitted), however, we found a similar switchover point where the deceleration times of

both hands were equal in both right- and left-hemisphere. This outcome suggests that the time devoted to feedback processing that might occur in the deceleration phase of the reach cannot account totally for limb selection as Stins et al. have proposed (2001). Instead, the data lead to the conclusion that the limb switching phenomenon was influenced significantly by the joint amplitudes associated with the control of the freely selected limb. Thus, the switch in limb from the dominant right-arm to non-dominant left-arm around  $80^\circ$  is associated with advantages linked to a reduction in the control of the reach from a two-joint to a single-joint movement.

In the present study, the comparison of free- and forced-choice limbs in kinematics revealed a symmetric pattern in the %DT data (see Fig. 4). The %DTs of the free left-arm and forced-right arm reaches intersected at position  $80^\circ$  in left-hemisphere, and at position  $100^\circ$  in right-hemisphere. Even though the free-arm had shorter MT in the lateral positions ( $50^\circ$ ,  $60^\circ$ ,  $70^\circ$ ,  $110^\circ$ ,  $120^\circ$ , and  $130^\circ$ ), the free-arm spent more time than the forced arm in the deceleration phase of the reach. Across medial positions of  $80^\circ$ ,  $90^\circ$ , and  $100^\circ$ , there were no differences between limbs with regard to amount of time devoted to feedback processing that might occur in the deceleration phase of the reach. This symmetric pattern of our %DT data seems to be more associated with the amplitude advantages of elbow (EA) and shoulder angle (SA) rather than a limb switching pattern.

More specifically, for right-handers, EAs of the free and forced limb were similar at positions of  $80^\circ$  and  $90^\circ$ . Also, SAs of the free and forced arm were similar at positions of  $80^\circ$  and  $90^\circ$ . These results were consistent with finding from our forced reaching study (Kim et al. 2007). As a target position moved away from the body midline, the freely

selected reaches were generated primarily by single-elbow motion, indicating a significant reduction from two-joint to single-joint in upper-arm motion to move the hand. In the left-hemisphere positions ( $50^\circ$  to  $80^\circ$ ), all positions showed a significant difference in EA between limbs except position of  $80^\circ$ . The right-arm may have an advantage up to our  $80^\circ$  position. With shoulder angle amplitude getting smaller in the left-arm, the advantage switches at position  $70^\circ$  when object proximity and a reduction in joint amplitudes combine to favor the nondominant left-arm. Furthermore, we also found similar aspect at position  $110^\circ$  for left-handers. Therefore, a key feature of the limb switching phenomenon in our study seems to be more linked to utilization of joints of the freely selected limb than times spent decelerating the limb.

Another key finding with regard to the limb switching phenomenon is the existence of a zone that gives an equal amount of kinematic advantages for both arms. We term this space *Zero Zone*, because of evidence that the positions in the middle area such as the position  $80^\circ$ ,  $90^\circ$ , and  $100^\circ$  showed similar kinematic profiles, indicating no kinematic advantages for either hand. As the target was moved away from the body midline, however, the kinematics suggest an advantage in the freely selected arm. In other words, the free-arm had significant kinematic advantages for position  $50^\circ$ ,  $60^\circ$ , and  $70^\circ$  in left-hemisphere and for position  $110^\circ$ ,  $120^\circ$ , and  $130^\circ$  in right-hemisphere among right-handed participants. We found this *Zero Zone* particularly in joint kinematics such as EA ( $80^\circ$  to  $90^\circ$ ) and the SA ( $80^\circ$  and  $90^\circ$ ). A similar aspect was also found in our left-handed participants. However, the *Zero Zone* of left-handers was somewhat different. Thus, the *Zero Zone* was shifted 10 degree more away from the body midline into right-hemisphere



compared to the Zero Zone of right-handers. Thus, we found the Zero Zone of left-handers with similar kinematics such as EA ( $90^\circ$  to  $110^\circ$ ) and SA ( $90^\circ$  to  $100^\circ$ ). For these positions, we found no difference in joint kinematics between the free- and forced-arm. Therefore, our data defined the Zero Zone as positions of  $80^\circ$  and  $90^\circ$  for right-handed participants and as positions of  $90^\circ$ ,  $100^\circ$ , and  $110^\circ$  for left-handed participants. After applying the concept of the Zero Zone to our target positions, for right-handers our target positions can be divided into three different zones: 1) Nondominant Zone ( $50^\circ$ ,  $60^\circ$ ,  $70^\circ$ ), 2) Zero Zone ( $80^\circ$  and  $90^\circ$ ), and Dominant Zone ( $100^\circ$ ,  $110^\circ$ ,  $120^\circ$ ,  $130^\circ$ ), whereas for left-handers our target positions can be divided into three zones: 1) Dominant Zone ( $50^\circ$ ,  $60^\circ$ ,  $70^\circ$ ,  $80^\circ$ ), 2) Zero Zone ( $90^\circ$ ,  $100^\circ$ ,  $110^\circ$ ), and Nondominant Zone ( $120^\circ$ ,  $130^\circ$ ). The boundaries between the Nondominant Zone and the Zero Zone were consistent with the switchover points in limb selection for both handedness groups. The boundary of the Zero Zone into contralateral hemispace for right-handers was 10 degree away from the body midline, whereas the boundary of the Zero Zone into contralateral hemispace for left-handers was 20 degree away from the body midline.

We thus suggest that kinematic advantages with regard to joint utilization drive limb selection in the Nondominant Zone and the Dominant Zone. On the other hand, when the advantages are equivalent for either hand (in the Zero Zone), it is plausible that there is no reason to select the nondominant-arm anymore and instead the dominant-arm could be easily selected. We therefore conclude that kinematic advantages with regard to a reduction in degrees of freedom for limbs are the primary factor for the limb switching bias around  $80^\circ$  for right-handers and  $110^\circ$  for left-handers. With similar kinematic advantages

(in the Zero Zone), motor dominance is the next influential factor for selecting limb. In sum, kinematic advantages with regard to a reduction in the control of the reach from a two-joint to a single-joint movement seem to be more adequate explanations for the limb selection phenomenon rather than time spent decelerating the action (Stins et al., 2001).

#### *Dynamic Dominance Hypothesis*

As proposed by the DDH (Sainburg, 2002), we predicted that the left arm/right hemisphere system would reveal more accurate final position in both handedness groups, regardless of object positions and sizes. If the right hemisphere/left arm system's greater role in position control exists, not only right-handers but also left-handers must show the left hand advantage in final position accuracy. However, we did not find evidence to support for the left-arm advantage of controlling final position. That is, for right-handers, the nondominant left-arm did not show any advantage for final position accuracy. Rather, the dominant right-arm had even more accurate final position for ipsilateral movements. For left-handers, on the other hand, there were no differences in final position error between the right- and left-arm for both ipsilateral and contralateral movements. As a result of the nonoccurrence of the right-arm advantage among left-handers, right-handers showed better accuracy than left-handers for most target positions. With regard to the dominant right-arm advantage in dynamic control of the hand-path trajectory, we predicted that the right arm/left hemisphere system would reveal greater performance in dynamic control of the hand-path trajectory for both handedness groups. For ipsilateral movements, however, we found no difference in hand path curvatures for left-handers, whereas for right-handers the dominant right-arm showed straighter hand-path than the nondominant

left-arm as target was moved into the body midline, indicating the left-arm disadvantage for performance of tasks that stress multi-joint movements rather than single-joint movements. Thus, we did not find differences in hand-path curvatures when participants employed single-joint reaching movements (i.e. ipsilateral reaching toward positions of Farthest and Far). For contralateral movements, which require more coordination of multi-segment dynamics, this left-arm disadvantage showed more clearly among right-handers rather than left-handers.

These results of final position accuracy and hand-path curvature are contradictory to the DDH and more consistent with the view that the dominant right-arm/left-hemisphere system shows superior performance in terms of speed, accuracy, consistency, and control over the nondominant arm (Annett, Annett, Hudson, & Turner, 1979; Flowers, 1975; Roy, 1983; Roy & Elliott, 1989; Todor & Doane, 1978; Woodworth, 1899). We did find that this right-arm/left-hemisphere advantage revealed more clearly among right-handers rather than left-handers and that right-handers showed better performance in final position accuracy than left-handers. This finding suggests that our left-handed data were consistent with one important implication from the right arm/left hemisphere advantage hypothesis in visually guided reaching and aiming movements. That is, failure to develop right-hand preference might reflect a failure to optimize visuomotor control. In other words, people who show left- or mixed-hand preference might be at a disadvantage for performance of tasks that stress visuomotor coordination of multi-segment dynamics with the dominant arm (Grouios, 2006)

Regardless of handedness and hand, final position errors varied systematically across target positions and increased as target position moved away from the body midline. This result suggests that final position errors were more dependent on target position. Target position was associated with greater changes in final position error than any other factors. The difference in PE between positions of Middle and Farthest was 0.38 cm for ipsilateral movements, and this difference by Position (0.38 cm) was almost 5 times greater than the difference by Handedness (0.08 cm) and almost 3 times greater than the difference by Size or Hand (0.12 cm). However, for contralateral movements, the difference in PE by position (0.07 cm) was almost 2 times less than the difference by Handedness (0.15 cm). Thus, the difference in PE between positions was significant only for ipsilateral movements. Because ipsilateral movements consisted of single-joint movements (mostly for positions of Farthest and Far) and two-joint movements (mostly for positions of Near to Middle), final position errors increased substantially when participant reached to the positions of Farthest and Far with a single-joint movement. On the other hand, contralateral movements consisted of only two-joint movements for all positions. These results indicated that an increment in final position errors seemed to be linked to a reduction in the control of the reach from a two-joint to a single-joint movement. Also, these findings indicate that Position and Hand are not the key determinant for final position accuracy. Therefore, we conclude that final position accuracy is more associated with a reduction in the control of the reach from a two-joint to a single-joint movement rather than a task-related condition such as a target position.

With inverse dynamic analysis, the contributions of elbow and shoulder joint torque to net torque for both handedness groups appeared to produce similar patterns. The contributions of elbow muscle torque to elbow net torque decreased substantially as the target was moved to the midline position. Along with it, the contribution of elbow interaction torques increased as a result of a reduction in elbow muscle torques. On the other hand, there was no substantial variation in elbow muscle torques in shoulder net torques. Thus, an increase in shoulder muscle torques was the primary cause for an increase in shoulder net torques. For right-handers, regardless of target positions, the contribution of elbow interaction torque impulse to elbow net torque impulse was almost 4% greater for dominant-arm movements as compared with nondominant-arm movements. Also, the contribution of elbow muscle torque impulse to net torque impulse was almost 2% less for right-arm movements. However, these data were not statistically significant.

Therefore, we did not find differences between the dominant- and nondominant-arm for IT, MuTe, and MuTs and these results indicated that there was no torque advantage of the dominant-arm for both right- and left-handed participants. Rather, our data suggested that joint torques were highly related to a target position. That is, interaction torques and shoulder muscle torques decreased as target position moved away from the body midline, whereas elbow muscle torques increased as target position moved away from the body midline. These results indicated that a reduction in the control of the reach from a two-joint (shoulder and elbow) to a single-joint (elbow) movement occurred as target position moved away from the body midline. Overall, the torque impulse of the dominant-arm movement, as compared to the nondominant-arm movements, did not reveal

less elbow muscle torque at the elbow and greater elbow muscle torque at the shoulder. We also found no significant torque differences between elbows among left-handers. As a result, we failed to prove the DDH that elbow muscle torque contributed essentially less toward the dominant left elbow movements.

In sum, our findings do not support the DDH, which suggest that the dominant arm is specialized for controlling limb dynamics to specify movement speed and hand-path curvatures. Also, our findings failed to prove the hypothesis that the nondominant arm is specialized for controlling final limb position during reaching movements. However, it should be noted that Sainburg's model was predicted on studies that have measured intersegmental dynamics with similar speeds for both limbs and used more rapid movements, which are more likely to be dependent on the control of intersegmental dynamics (Bagesteiro & Sainburg, 2002; Haaland et al., 2004; Sainburg, 2002; Sainburg & Kalakanis, 2000). Our data indicated that right- and left-arm reaching movements occurred with different speeds for each arm. Therefore, it is still unclear whether the difference between Sainburg's hypothesis and our data emerged from distinct hemispheric specialization or from a secondary effect of different kinematics. This notion was considered and applied in Study 2 by controlling for the speed of the reach.

### CHAPTER III

#### STUDY 2: LIMB ACTION

Arguably, the *Dynamic Dominance Hypothesis* (DDH) is one of the most acknowledged perspectives in handedness studies. The DDH focuses on interlimb differences with the general idea that the two arms are differentially specialized for actions (Bagesteiro & Sainburg, 2002; Sainburg, 2002). More specifically, this notion proposes that each hemisphere limb system is specialized for selecting and controlling different features of a reaching action. In other words, even among strongly lateralized right-handers, the non-dominant left limb is advantageous in specific situations. That is, the dominant arm is specialized for controlling limb dynamics as required to specify movement speed and hand-path curvatures, whereas the nondominant arm is specialized for controlling static limb position as required to specify the final position during reaching movements (Bagesteiro & Sainburg, 2002, 2003; Duff & Sainburg, 2007; Heuer, 2007; Sainburg, 2002, 2005; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2007).

The previous study (Study 1) did not support a generalization of the DDH to left-handers. Thus, controlling limb dynamics and utilizing torques between the dominant- and nondominant-arm were not significantly different. In addition, the nondominant arm did not reveal advantages for controlling static limb position (final position) during reaches. Rather, the dominant arm showed better performance in final position accuracy. Therefore, we concluded that the view of the right-arm/left-hemisphere advantage was a more adequate explanation for limb difference rather than the DDH. Also, we found that the

DDH was an inadequate explanation for the limb selection phenomenon. As an alternative explanation, we suggested a reduction in degrees of freedom for reaching with regard to the Zero Zone hypothesis, indicating that participants primarily select the dominant arm unless kinematic and kinetic advantages for the nondominant arm exist. However, the difference between the DDH and our data was still unclear because we do not know whether this difference emerged from distinct hemispheric specialization or from a secondary effect of different kinematics. In the previous studies by Sainburg et al. (Bagesteiro & Sainburg, 2002, 2003; Duff & Sainburg, 2007; Sainburg, 2002, 2005; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2007), most reaching movements were performed at the participant's elected natural speed within an interval of 400-600 ms and the right and left hands showed a similar time course for all participants (Bagesteiro & Sainburg, 2002; Bagesteiro & Sainburg, 2003; Sainburg, 2002; Sainburg & Kalakanis, 2000). Thus, Sainburg's model suggests that more rapid movements may require a change in the control of intersegmental dynamics. In order to identify the difference between Sainburg's hypothesis and our data, we designed Study 2 to examine the speed of the reaching action. That is, we manipulated limb speed using slow (1500 ms) and fast (550 ms) moving targets.

The primary intent of Study 2 was to examine the effect of a change in speed (from participant's elected natural speed) on limb selection and in the underlying limb kinematics and kinetics. Furthermore, it is also important to understand how a change in speed affects the DDH as well as limb selection. Therefore, the purpose of this study was to explore the following questions: *“Does a wide range of speed (slow and fast) affect limb selection?”* If



so, “*does a change in speed fit the DDH?*” Reaching movements were made to each of nine targets using free-choice and forced-choice paradigms in order to compare both arms. In order to identify the advantages of each arm, nine target positions were divided into five new positions for testing the DDH. Each new position consisted of two target positions, which produce anatomically and mechanically homologous movements for both arms.

We predicted that the percentage of the dominant-arm use would increase when the fast target was presented. As a result, we assumed that a change in the limb switchover point between the dominant- and nondominant-arm would occur when the fast target was presented compared to when the slow target was presented. That is, the switchover point would shift further into the contralateral hemispace from the body midline when the fast target was presented. Also, we predicted that the free arm would show differences in amplitudes of joint angles compared to the forced arm. Thus, we predicted that a change of the switchover point in limb selection as a result of a change in speed would affect kinematic and kinetic variables.

## **Method**

### *Participants*

10 right-handed and 10 left-handed adults, ages 19 to 23 years old, participated in the present study. The participation was limited to strong right- and left-handers; that is, only those individuals that used their right or left hand consistently with all four preference tasks as described in the Lateral Preference Inventory (Coren 1993). The experimental protocol and consent form were approved by the Texas A&M Institutional Review Board (IRB) for the ethical treatment of human subjects. The participants were informed of the

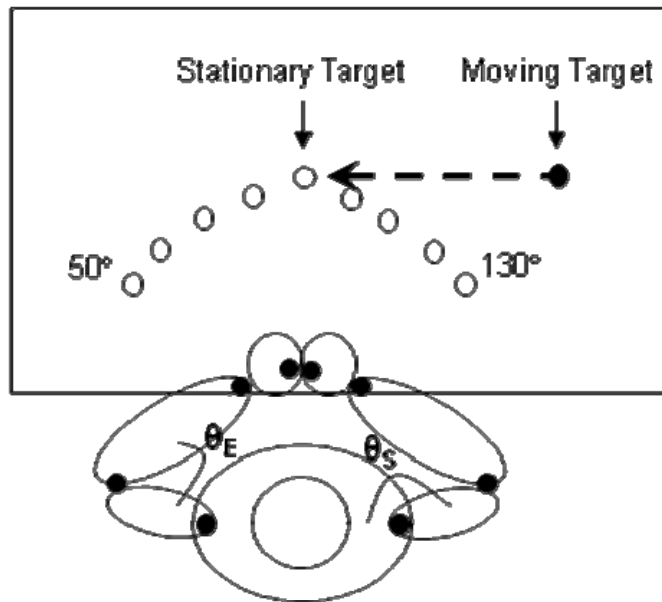
experimental procedures and risk level and voluntarily signed a consent form before participating in this study.

### *Procedures*

Procedures and apparatus were the same as shown in Study 1 except for the task. Contrary to participant's elected natural speed in Study 1, the speed of reaching was controlled for this task. Participants were instructed to execute reaching movements in order to point to a circle target shown on a tabletop at 9 different positions: the body midline (labeled 90°), 80°, 70°, 60° and 50° to the left, and 100°, 110°, 120°, 130° to the right of the body midline. Participants were instructed to perform a reach and point action coincidentally with a horizontally moving target that moved from the side of the display toward the stationary target (50 cm identical moving distance for all positions and participants). The slow (1500 ms) and fast (550 ms) moving targets were randomly presented regardless target circle position. The stationary target and the moving target were 1 cm in diameter white circles displayed by a projector mounted in the ceiling (Fig. 18).

### *Apparatus*

The same testing apparatus was used as described for Study 1.



**Figure 18.** View of the experimental set-up for Study 2. Acronyms indicate following:  $\theta_E$ -elbow angle,  $\theta_S$ -shoulder angle.

### *Data Analysis*

The same measures were used as described for Study 1.

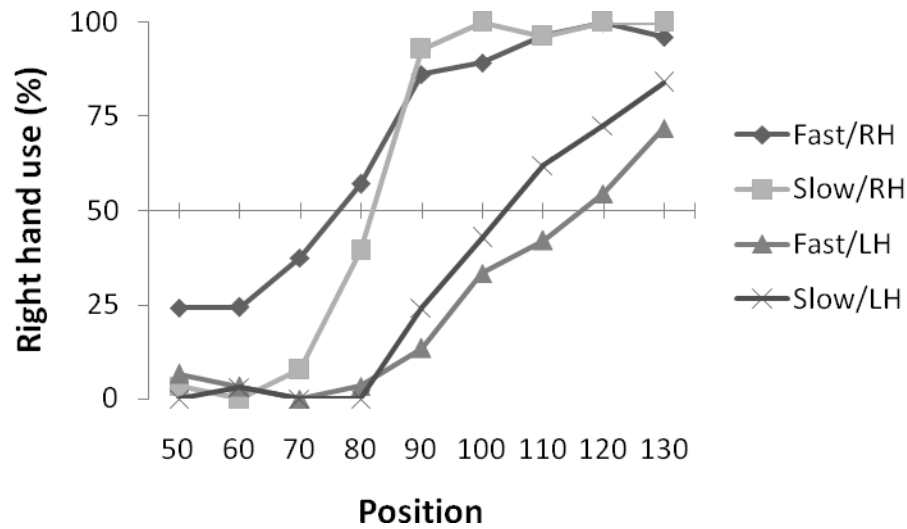
## **Results**

### *Limb Selection*

The percentage of free-choice reaches executed with the right hand as a function of Position ( $50^\circ$  to  $130^\circ$ ), Target Speed (slow vs. fast), and Handedness (right- vs. left-handers) is illustrated in Figure 19. A three-way ANOVA revealed main effects for Handedness,  $F(1, 32) = 24.7, p < .01$ , and Position,  $F(8, 32) = 8.2, p < .01$ . Also, we found interactions of Handedness  $\times$  Speed,  $F(1, 32) = 22.6, p < .01$ , Speed  $\times$  Position,  $F(8, 32) = 6.6, p < .01$ , and Handedness  $\times$  Position,  $F(8, 32) = 21.4, p < .01$ , with no other main

effects or interaction effects found. Simple main effect analysis for the Speed  $\times$  Handedness interaction revealed that right-handers (67%) showed significantly greater right-arm use than left-handers (25%) for the fast target. Also, simple main effect analysis for the Speed  $\times$  Position interaction revealed no differences of right hand use between the slow and fast targets for each position. Another simple main effect analysis for the Handedness  $\times$  Position interaction revealed that right-handers had greater right-hand use than left-handers when reaching for positions 70° to 120°.

Overall, with the fast target condition, our right-handed participants performed an equal number of free right-arm and free left-arm reaches to the position of 80°. Free left-arm reaches dominated across positions 50° to 70° in left hemi-space, and free right-arm reaches dominated at position 90°, and from position 100° to 130° in right-hemisphere. On the other hand, with the slow target condition, a similar profile was found in right-hemisphere but substantially different in left-hemisphere. Thus, the crossover point of an equal number of free right-arm and free left-arm reaches occurred at position 80°. We also found that right-hand use increased in left-hand dominant hemisphere compared to the slow target condition. This result indicated that target speed influenced limb selection preference and the fast target condition changed the crossover point 10° away from the body midline compared to the slow target condition (Fig. 19).

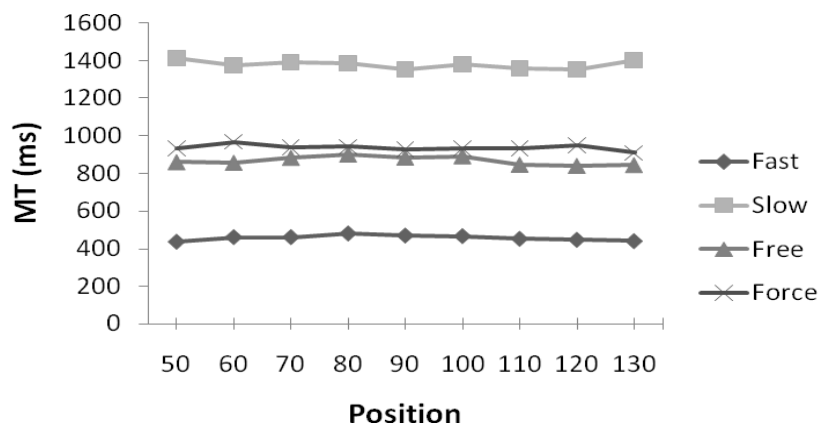


**Figure 19.** Percentage of reaches executed with the right arm for Study 2. The point on the abscissa corresponding to where the 50% line crosses the curve for each condition marks the point at where both hands were used equally often.

### *Limb Kinematics*

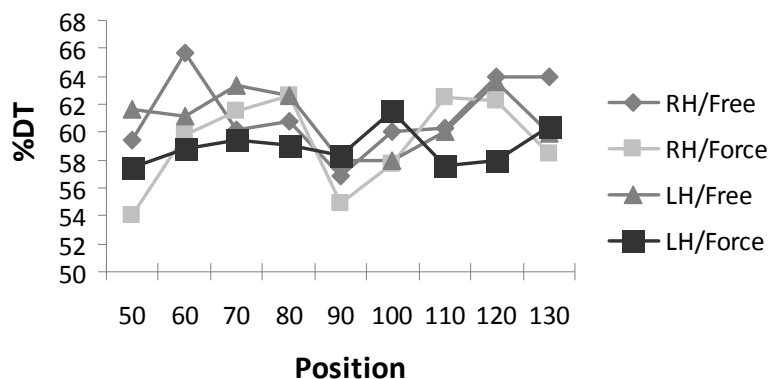
*Movement time (MT).* In order to identify a relationship between limb selection and kinematics of limbs, we performed four-way ANOVAs for MT, %DT, EA, and SA as a function of Position (50° to 130°), Handedness (right- vs. left-handers), Speed (slow vs. fast), and Selection (Free vs. Forced). First of all, the ANOVA for MT revealed main effects for Handedness,  $F(1, 1926) = 142, p < .01$ , Speed,  $F(1, 1926) = 17546, p < .01$ , and Selection,  $F(1, 1926) = 223, p < .01$ . Thus, left-handers (863 ms), the fast target condition (456 ms), and the free-arm (867 ms) had shorter MTs than right-handers (944 ms), the slow target condition (1378 ms), and the forced-arm (938 ms). Simple main effect analyses for the Speed  $\times$  Selection interaction  $F(1, 1926) = 28.2, p < .01$ , revealed that the free-arm

(423 ms) had shorter MTs than the forced-arm (490 ms) when reaching for the fast target. Also, the free-arm (1315 ms) had shorter MTs than the forced-arm (1452 ms) for the slow target. However, the differences between the free- and forced-arm were greater when reaching for the slow target (136 ms) than for the faster target (67 ms). Simple main effect analyses for the Handedness  $\times$  Speed interaction,  $F(1, 1926) = 110, p < .01$ , revealed that left-handers (1305 ms) had shorter MTs than right-handers (1462 ms) only when reaching for the slow target, whereas there was no difference in MT between handedness groups when reaching for the faster target,  $p > .05$ . We also found a Position  $\times$  Speed interaction  $F(8, 1926) = 2.4, p < .05$ , and a Position  $\times$  Selection interaction  $F(8, 1926) = 2.5, p < .01$ . Simple main effect analyses for these interactions revealed that the free-arm was not significantly faster than the forced-arm for all positions, whereas the fast target showed shorter MTs than the slow target for all positions (Fig. 20).



**Figure 20.** Movement times (MT) plotted as a function of Position, Speed and Selection for Study 2.

*Deceleration time (%DT)*. The ANOVA for %DT revealed main effects for Position,  $F(8, 1926) = 4.4, p < .01$ , Speed,  $F(1, 1926) = 699, p < .01$ , and Selection,  $F(1, 1926) = 5.9, p < .01$ . Thus, these results indicated that the free-arm (61%) and the slow target condition (67%) had greater time associated with deceleration than the forced-arm (59%) and the fast target condition (53%) regardless of Position and Handedness. Simple main effect analyses for the Speed  $\times$  Selection interaction  $F(1, 1926) = 18.8, p < .01$ , revealed that the free-arm (55%) had greater %DT than the forced-arm (51%) when reaching for the fast target. However, the free-arm (67%) showed no difference in %DT from the forced-arm (68%) when reaching for the slow target. Another simple main effect analyses for the Handedness  $\times$  Speed interaction,  $F(1, 1926) = 17, p < .01$ , revealed that left-handers (54%) had greater %DT than right-handers (52%) when reaching for the fast target, whereas right-handers (69%) had greater %DT than left-handers (66%) when reaching for the slow target. Also, we found a three-way interaction for Position  $\times$  Handedness  $\times$  Selection,  $F(8, 1926) = 2, p < .05$ . Simple main effect analyses for the interaction revealed that for right-handers the free-arm had greater %DT than the forced-arm when reaching for position 50°, 60°, and 130°. On the other hand, for left-handers the free-arm had greater %DT than the forced-arm for position 50° and 120° (Fig. 21).

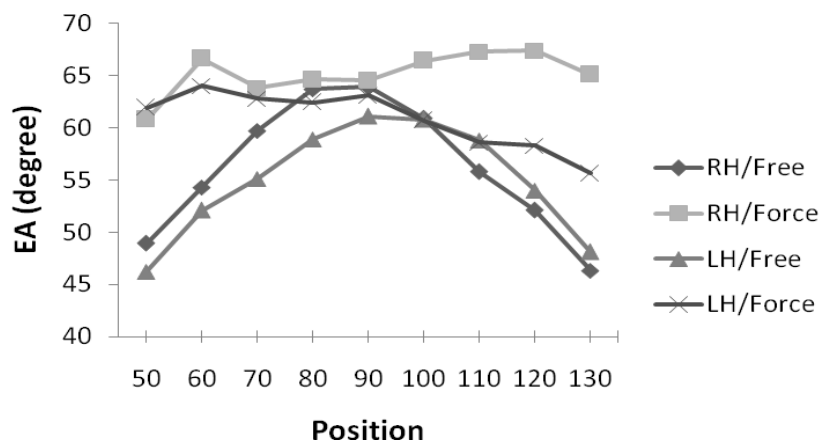


**Figure 21.** Percentages of deceleration times (%DT) plotted as a function of Position, Handedness, and Selection for Study 2.

*Joint angles (EA and SA).* We found significant main and interaction effects for EA and SA as a function of Position, Handedness, Speed, and Selection. First, the ANOVA for EA revealed main effects for Position,  $F(8, 1926) = 32.6, p < .01$ , Handedness,  $F(1, 1926) = 50.9, p < .01$  and Selection,  $F(1, 1926) = 371.8, p < .01$ . We also found interactions for Position  $\times$  Selection,  $F(8, 1926) = 18, p < .05$ , Handedness  $\times$  Selection,  $F(1, 1926) = 17.1, p < .01$ , and a three-way interaction for Position  $\times$  Handedness  $\times$  Selection,  $F(8, 1926) = 8.2, p < .01$ . Simple main effect analyses for the three-way interaction revealed that for right-handers the free-arm had significantly less EA than the forced-arm for positions  $50^\circ$  to  $70^\circ$ , and for positions  $100^\circ$  to  $130^\circ$ , whereas for left-handers the free-arm had significantly less EA than the forced-arm for positions  $50^\circ$  to  $80^\circ$ , and for positions  $120^\circ$  and  $130^\circ$  (Fig. 22). Another simple main effect analyses for the Handedness  $\times$  Selection interaction,  $F(1, 1926) = 5.7, p < .05$ , revealed that the free-arm showed significantly less



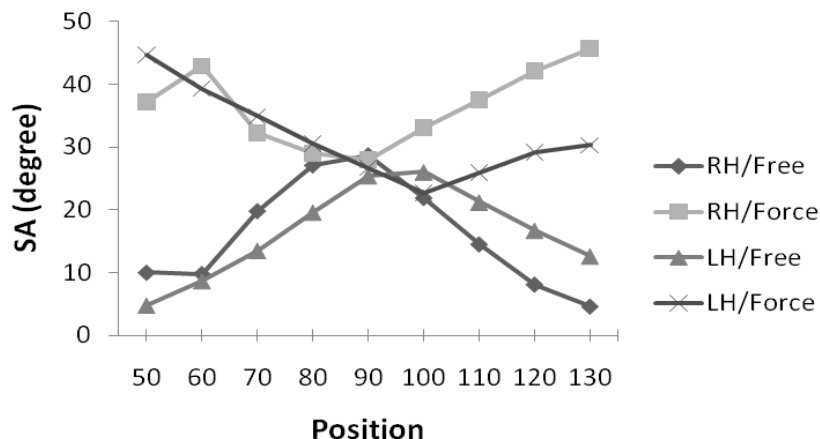
EA than the forced-arm for both right-handers (56 vs. 65°, respectively) and left-handers (55 vs. 61°, respectively). However, the differences of EA between the free- and forced-arm were greater for right-handers (9°) than for left-handers (5°) (Fig. 22).



**Figure 22.** Elbow angle amplitudes (EA) plotted as a function of Position, Handedness, and Selection for Study 2.

The ANOVA for SA revealed main effects for Position,  $F(8, 1926) = 2.9, p < .01$ , Handedness,  $F(1, 1926) = 20.7, p < .01$ , and Selection,  $F(1, 1926) = 1246, p < .01$ . Also, we found interactions for Position  $\times$  Selection,  $F(8, 1926) = 69.3, p < .01$ , Handedness  $\times$  Selection,  $F(1, 1926) = 28.6, p < .01$ , and a three-way interaction for Position  $\times$  Handedness  $\times$  Selection,  $F(8, 1926) = 21.6, p < .01$ . Simple main effect analyses for the three-way interaction revealed that for right-handers the free-arm showed significantly less SA than the forced-arm when reaching for positions 50° to 70°, and for positions 100° to

130°. On the other hand, for left-handers the free-arm had significantly less SA than the forced-arm for positions 50° to 80°, and for positions 110° to 130° (Fig. 23).

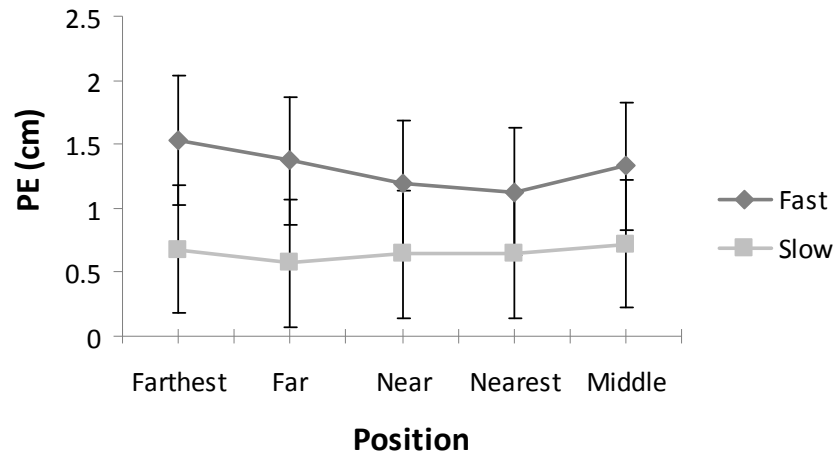


**Figure 23.** Shoulder angle amplitudes (SA) plotted as a function of Position, Handedness, and Selection for Study 2.

#### *Movement Accuracy*

*Final position error (PE).* In order to identify movement accuracy advantage for the nondominant arm as indicated in the DDH, we performed separate four-way ANOVAs (ipsilateral and contralateral) for PE and DL as a function of 5 Position (Farthest: 50 and 130°, Far: 60 and 120°, Near: 70 and 110°, Nearest: 80 and 100°, Middle: 90°), 2 Handedness (right- vs. left-handers), 2 Speed (slow vs. fast), and 2 Hand (dominant vs. nondominant). First of all, for ipsilateral movements, the ANOVA for PE revealed main effects for Position,  $F(4, 1139) = 4.3, p < .01$ , and Speed,  $F(1, 1139) = 343.6, p < .01$ . We

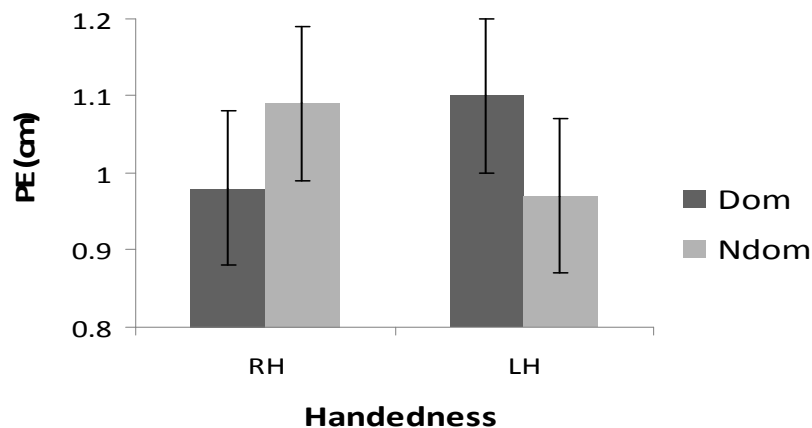
also found an interaction for Position  $\times$  Speed,  $F(4, 1197) = 3.3, p < .01$ . Simple main effect analyses for the interaction revealed greater accuracy in final position for the slow target compared to the fast target for all positions (Fig 24).



**Figure 24.** Final position error (PE) for ipsilateral movements plotted as a function of Position and Speed for Study 2.

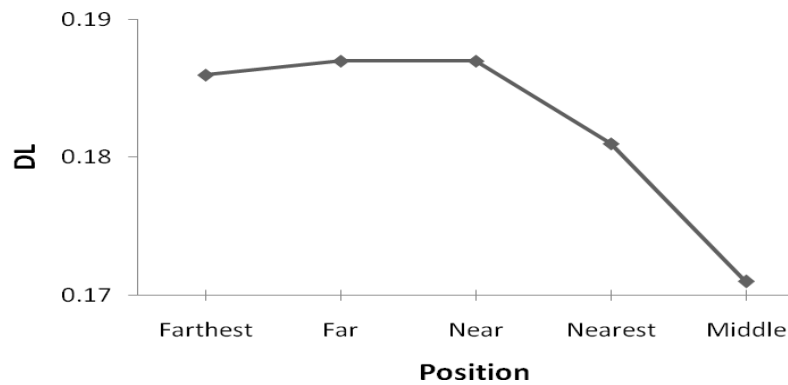
For contralateral movements, the ANOVA for PE revealed a main effect for Speed,  $F(1, 1015) = 188, p < .01$ . We also found an interaction for Handedness  $\times$  Speed,  $F(1, 1015) = 6, p < .05$ , and Handedness  $\times$  Hand,  $F(1, 1015) = 5.5, p < .05$ . Simple main effect analyses for the Handedness  $\times$  Speed interaction revealed that left-handers (1.2 cm) showed more accurate final position than right-handers (1.3 cm) for the fast target condition, whereas there was no significant difference of PE between handedness groups for the slow target condition. The simple main effect analyses for the Handedness  $\times$  Hand interaction revealed that for left-handers the nondominant right-arm was more accurate

than the dominant left-arm, whereas for right-handers the dominant right-arm was more accurate than the nondominant left-arm (Fig 25).



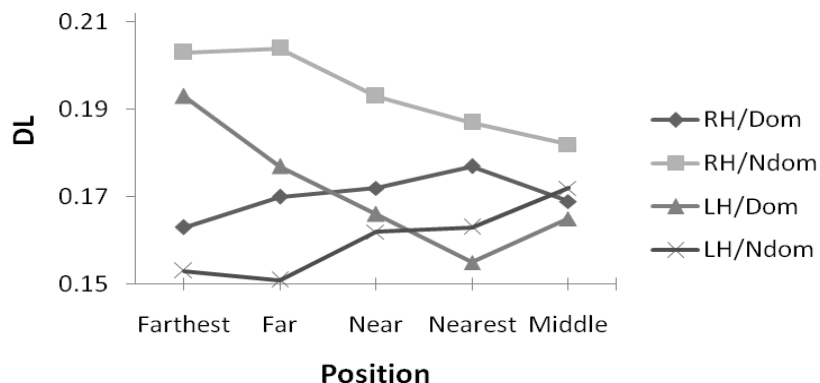
**Figure 25.** Final position error (PE) for contralateral movements plotted as a function of Hand and Handedness for Study 2.

*Deviation from linearity (DL).* For ipsilateral movements, the ANOVA for DL revealed main effects for Position,  $F(4, 1139) = 3.4, p < .01$ , Handedness,  $F(1, 1139) = 16.8, p < .01$ , Hand,  $F(1, 1139) = 5.3, p < .01$ , and Speed,  $F(1, 1139) = 16, p < .01$ , and no interaction effects were found. These results indicated that the dominant-arm (0.17) produced a straighter hand-path than the nondominant-arm (0.18), that left-handers (0.17) had straighter hand-paths than right-handers (0.19), and that the slow target condition (0.17) had straighter hand-path than the fast target condition (0.18). Post-hoc analysis from the Position effect revealed that the position Middle was significantly different from the position Near,  $p < 0.5$  (Fig. 26).



**Figure 26.** Deviation from linearity (DL) for ipsilateral movements plotted as a function of Position for Study 2.

For contralateral movements, the ANOVA for DL revealed main effects for Handedness,  $F(1, 1015) = 29.8, p < .01$ , Hand,  $F(1, 1015) = 8.7, p < .01$ , and Speed,  $F(1, 1015) = 17.5, p < .01$ . We found an interaction for Handedness  $\times$  Hand,  $F(1, 1015) = 53.4, p < .01$ , as well as a three-way interaction for Position  $\times$  Handedness  $\times$  Hand,  $F(4, 1015) = 6.8, p < .01$ . Simple main effect analyses for the interaction revealed that for right-handers the dominant-arm had straighter hand-path than the nondominant-arm for position Farthest, Far, and Near. On the other hand, for left-handers the nondominant-arm had straighter hand-path than the dominant-arm for position Farthest and Far (Fig. 27).

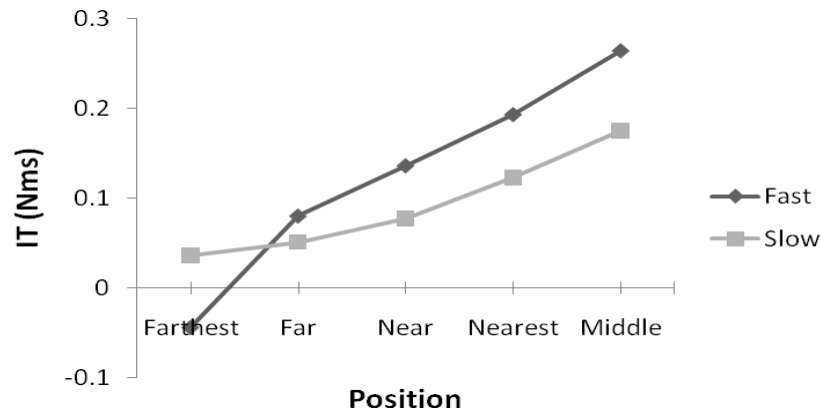


**Figure 27.** Deviation from linearity (DL) for contralateral movements plotted as a function of Position, Handedness and Hand for Study 2.

### *Limb Kinetics*

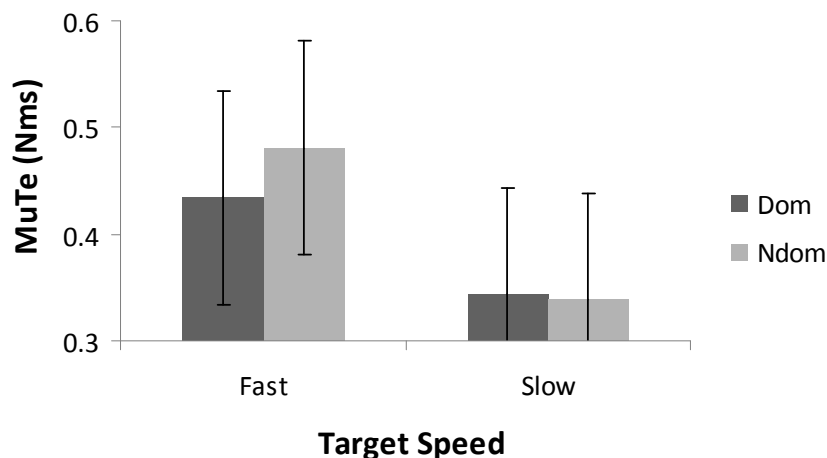
In order to identify efficient torque advantage for the dominant arm as indicated in the DDH, we performed separate four-way ANOVAs (ipsilateral and contralateral) for IT, MuTe and MuTs as a function of 5 Position (Farthest: 50 and 130°, Far: 60 and 120°, Near: 70 and 110°, Nearest: 80 and 100°, Middle: 90°), 2 Handedness (right- vs. left-handers), 2 Speed (slow vs. fast), and 2 Hand (dominant vs. nondominant).

For ipsilateral movements, first of all, the ANOVA for IT revealed main effects for Position,  $F(4, 1139) = 46.8, p < .01$ , and Speed,  $F(1, 1139) = 9.4, p < .01$ , and an interaction for Position  $\times$  Speed,  $F(4, 1139) = 7, p < .01$ . Simple main effect analyses for the interaction revealed that the fast target showed greater IT than the slow target for position Near, Nearest, and Middle (Fig. 28).



**Figure 28.** Interaction torque impulses (IT) for ipsilateral movements plotted as a function of Position and Speed for Study 2.

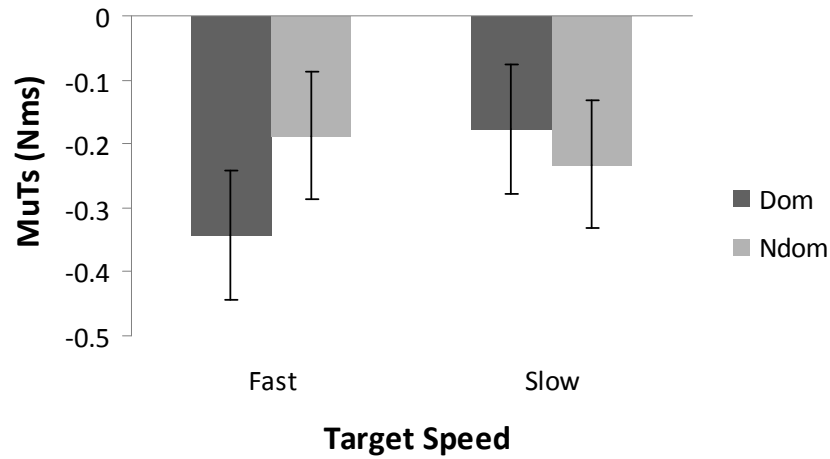
The ANOVA for MuTe revealed a main effect for Position,  $F(4, 1139) = 5, p < .01$ , Speed,  $F(1, 1139) = 82.3, p < .01$ , and an interaction for Hand  $\times$  Speed,  $F(1, 1139) = 3.8, p < .05$ . Simple main effect analyses for the interaction revealed that the dominant-arm (0.43 Nms) had less MuTe than the nondominant-arm (0.48 Nms) for the fast target, whereas there was no difference between the dominant-arm (0.34 Nms) and the nondominant-arm (0.33 Nms) for the slow target (Fig. 29).



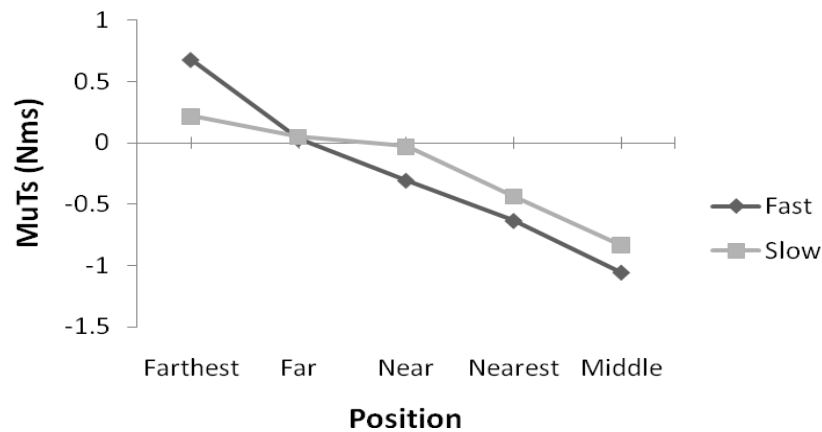
**Figure 29.** Muscle torque impulses of the elbow (MuTe) for ipsilateral movements plotted as a function of Hand and Speed for Study 2.

For MuTs, we found a main effect for Position,  $F(1, 1139) = 139, p < .01$ , and interactions for Position  $\times$  Speed,  $F(4, 1139) = 10.7, p < .01$ , and Hand  $\times$  Speed,  $F(4, 1139) = 5.8, p < .05$ . Simple main effect analyses for the Hand  $\times$  Speed interaction revealed that the dominant-arm (-0.34 Nms) had greater MuTs than the nondominant-arm (-0.18 Nms) for the fast target, whereas there was no difference between the dominant-arm (-0.17 Nms) and the nondominant-arm (-0.23 Nms) for the slow target (Fig. 30). Also, simple main effect analyses for the Position  $\times$  Speed interaction revealed that the fast target condition showed greater MuTs than the slow target condition for position Farthest, Near, Nearest, and Middle (Fig. 31). Overall, there were no main effects for Hand on MuTe and MuTs,  $p > .05$ , and these results indicated that there were no muscle torque advantages of the dominant-arm for both handedness groups.





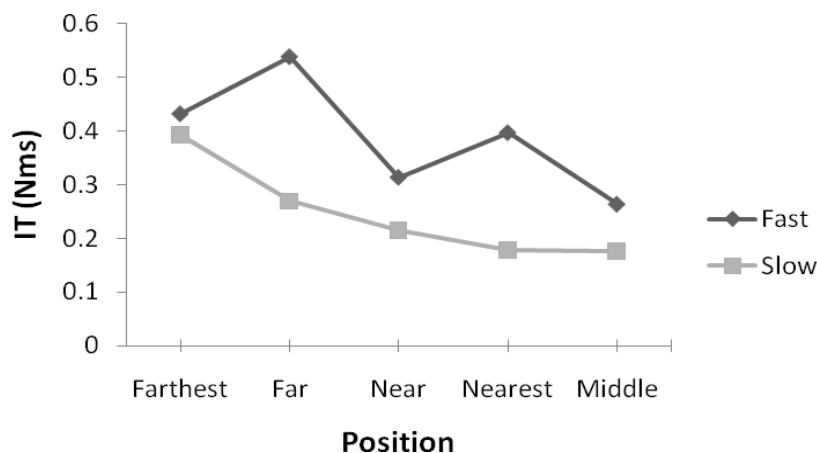
**Figure 30.** Muscle torque impulses of the shoulder (MuTs) for ipsilateral movements plotted as a function of Hand and Speed for Study 2.



**Figure 31.** Muscle torque impulses of the shoulder (MuTs) for ipsilateral movements plotted as a function of Position and Speed for Study 2.

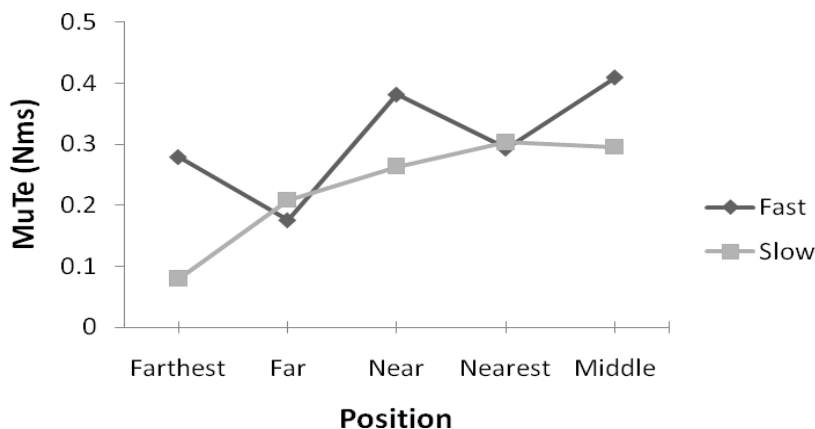
For contralateral movements, the ANOVA for IT revealed main effects for Position,  $F(4, 1015) = 8.9, p < .01$ , and Speed,  $F(1, 1015) = 27.7, p < .01$ , and an interaction for

Position  $\times$  Speed,  $F(4, 1015) = 3, p < .05$ . Simple main effect analyses for the interaction revealed that the fast target showed greater IT than the slow target for position Far and Nearest (Fig. 32).



**Figure 32.** Interaction torque impulses (IT) for contralateral movements plotted as a function of Position and Speed for Study 2.

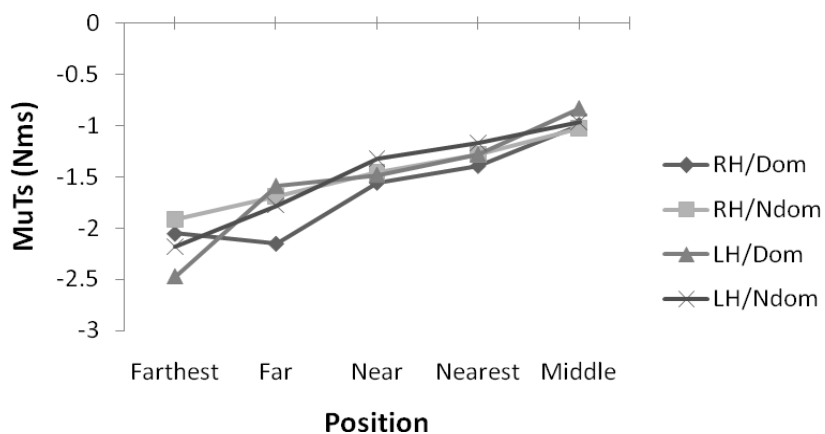
The ANOVA for MuTe revealed main effects for Position,  $F(4, 1015) = 7.1, p < .01$ , Hand,  $F(1, 1015) = 4.1, p < .05$ , Handedness,  $F(1, 1015) = 5.4, p < .05, p < .01$ , Speed,  $F(1, 1015) = 9.4, p < .01$ , and an interaction for Position  $\times$  Speed,  $F(4, 1015) = 2.8, p < .05$ . Thus, the dominant-arm (0.25 Nms) had slightly less MuTe than nondominant-arm (0.29 Nms) and simple main effect analyses for the interaction revealed that the slow target condition showed less MuTe than the fast target condition for position Farthest, Near, and Middle (Fig. 33).



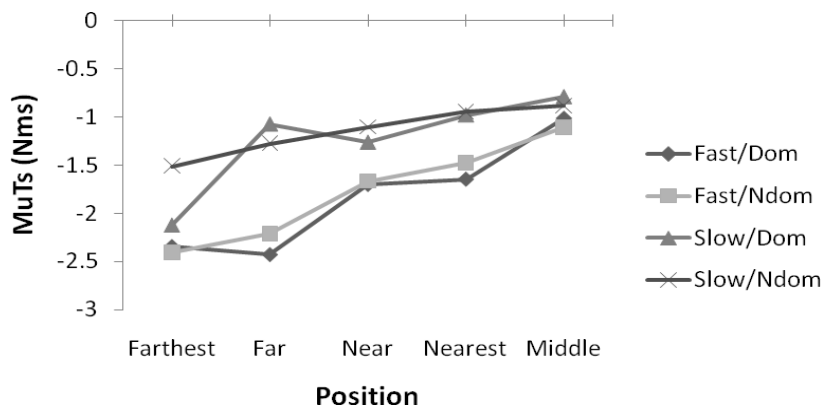
**Figure 33.** Muscle torque impulses of the elbow (MuTe) for contralateral movements plotted as a function of Position and Speed for Study 2.

For MuTs, we found main effects for Position,  $F(4, 1015) = 53, p < .01$ , and Speed,  $F(1, 1015) = 123, p < .01$ . Thus, the fast target (-1.78 Nms) showed greater MuTs than the slow target (-1.13 Nms). We found an interaction for Position  $\times$  Handedness,  $F(4, 1015) = 3.3, p < .01$ , and a three-way interaction for Position  $\times$  Handedness  $\times$  Hand,  $F(4, 1015) = 2.4, p < .05$ . Simple main effect analyses for the interaction revealed that for right-handers the dominant-arm (-2.1 Nms) had greater MuTs than the nondominant-arm (-1.6 Nms) for position Far, whereas for left-handers there were no differences of MuTs between the dominant- and nondominant-arm for all positions (Fig. 34). We also found an interaction for Position  $\times$  Speed,  $F(4, 1015) = 8.6, p < .01$ , and a three-way interaction for Position  $\times$  Speed  $\times$  Hand,  $F(4, 1015) = 2.6, p < .05$ . Simple main effect analyses for the interaction revealed that for the slow condition the dominant-arm (-2.1 Nms) had greater MuTs than the nondominant-arm (-1.5 Nms) only for position Farthest. For the fast condition,

however, we found no differences of MuTs between the dominant- and nondominant-arm for all positions (Fig. 35).



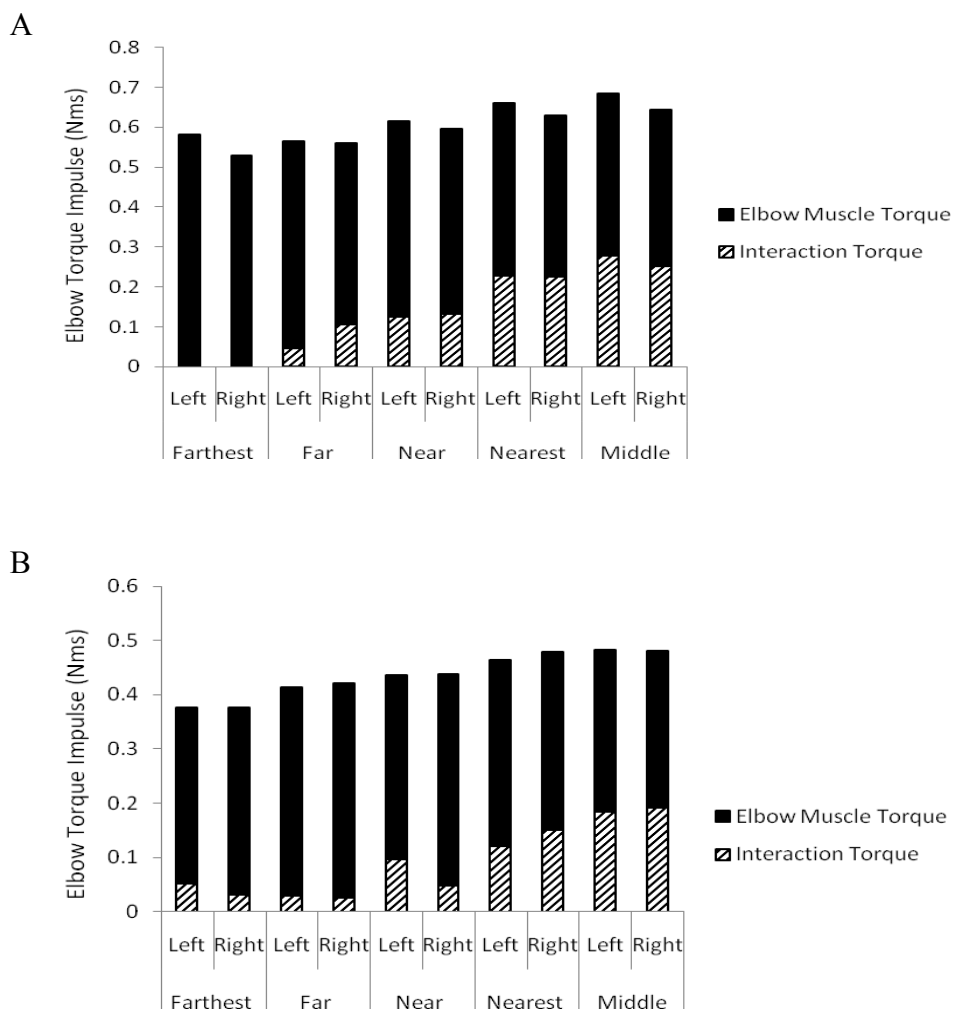
**Figure 34.** Muscle torque impulses of the shoulder (MuTs) for contralateral movements plotted as a function of Position, Handedness and Hand for Study 2.



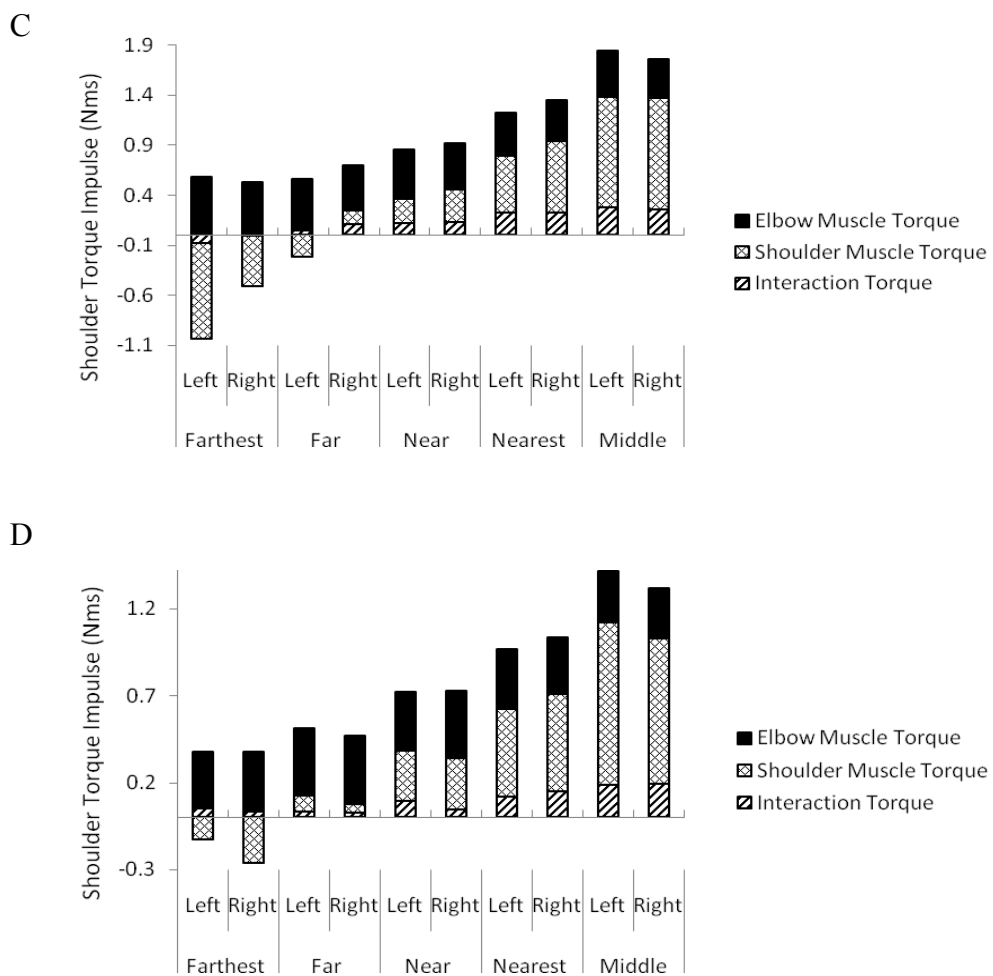
**Figure 35.** Muscle torque impulses of the shoulder (MuTs) for contralateral movements plotted as a function of Position, Speed, and Hand for Study 2.

Interlimb differences in torque contributions illustrated by the stacked bar plots are shown in Fig. 36; measured as separate contributions to shoulder and elbow net torque. The contribution to NTe consisted of MuTe and IT, and the contribution to NTs consisted of MuTe in addition to MuTs and IT. In order to obtain torque impulses, original shoulder and elbow torques derived from the equations were integrated from movement onset to movement offset. Net joint torque was equal to the summed positive and negative bar plot height. With regard to speed, we found that reaches to the fast target made greater MuTe, MuTs, and IT regardless of positions and hands. We did not find a significant difference between the right and left hands for each joint torques,  $p > .05$ , but we found a substantial difference between NTe and NTs profiles. That is, NTe did not vary across target positions and did not show a difference between hands, whereas NTs varied across target positions. Thus, NTs decreased substantially as target position moved away from the body midline ( $90^\circ$ ). This result indicates that NTs are associated mostly with amplitudes of shoulder joint angle. The contributions of MuTe to NTe increased substantially as target position moved away from the body midline. Along with it, the contribution of IT decreased as a result of an increment in MuTe. On the other hand, there was no substantial variation in the contribution of MuTe to NTs. Thus, an increase in MuTs was the primary cause for an increase in NTs. Regardless of the target positions and speeds, the contribution of MuTe to NTe was a little smaller for right-arm movements as compared to left-arm movements, but not significant ( $p > .05$ ). In other words, this data indicated that the contribution of MuTe and IT to NTe showed no significant difference between the right and left arm. On the contrary to the results of Sainburg et al., our data suggested that MuTe did not contribute

essentially less toward right elbow movements. As a result, we failed to support the DDH for the dominant right-arm advantages, as compared with the nondominant left-arm movements.



**Figure 36.** Muscle and interaction torque impulse plotted as a contribution to net torque for the elbow joint (A: fast target, B: slow target) and for the shoulder joints (C: fast target, D: slow target) for Study 2.



**Figure 36.** Continued

## **Discussion**

The primary intent of Study 2 was to further investigate generalization of the DDH under conditions of controlled reaching speed, slow and fast. Also, this study further examined the difference between the DDH and our data with regard to the view that each hemisphere/limb system is specialized for unique processes. That is, the dominant arm system is specialized for controlling limb dynamics, and the nondominant arm system is specialized for controlling final limb position. More specifically, this study addressed the following questions: “*will the speeds of the reach change limb selection?*” If so, “*does this change affect the control efficiency of the limb?*”

### *Limb Selection*

We predicted that the percentage of dominant-arm use would increase when the fast target was presented. As a result, we assumed that a change in the limb switchover point between the dominant- and nondominant-arm would occur when the fast target was presented compared to when the slow target was presented. That is, the switchover point would shift further into the contralateral hemispace from the body midline when the fast target was presented. Also, we predicted that the free arm would show differences in amplitudes of joint angles compared to the forced arm. Thus, we predicted that a change of the switchover point in limb selection as a result of a change in speed would affect kinematic and kinetic variables.

As expected, we found that the target speed influenced limb selection preference. That is, our right-handed participants showed that their switchover point in limb selection was shifted 10° further into left-hemispace and our left-handed participants revealed that



their switchover point was shifted  $10^\circ$  further into right-hemisphere when the fast target was presented. These similar hand preference profiles for both handedness groups indicated that target speed is a more influential factor in limb selection than target size and that this bias is substantially identical between handedness groups.

The comparison of free- and forced-choice limbs in kinematics revealed a symmetric pattern in the %DT data as found in our previous study (Study 1). The %DTs of the free left-arm and the forced-right arm reaches started merging into position  $80^\circ$  in left-hemisphere and continuing up to  $110^\circ$ . Even with similar movement times for all positions, the free arm for the most lateral positions in hemispaces spent more time in the deceleration phase of the reach than the forced arm. For the medial positions of  $80^\circ$ ,  $90^\circ$ ,  $100^\circ$ , and  $110^\circ$ , there were no differences between limbs with regard to the amount of time devoted to feedback processing that might occur in the deceleration phase of the reach. This symmetric pattern in our %DT data seems to be more associated with the amplitude advantages of elbow angle (EA) and shoulder angle (SA) rather than a limb switching pattern.

More specifically, for right-handers, EAs of the free and forced limb were similar at positions of  $80^\circ$  and  $90^\circ$ . Also, SAs of the free and forced arm were similar at positions of  $80^\circ$  and  $90^\circ$ . These results were consistent with the findings from Study 1. As a target position moved away from the body midline, the freely selected reaches were generated primarily by single-elbow motion, indicating a significant reduction from two-joint to single-joint in upper-arm motion to move the hand. In the left-hemisphere positions ( $50^\circ$  to  $80^\circ$ ), all positions showed a significant difference in EA between limbs except position of

80°. The right-arm may have an advantage up to our 80° position. With shoulder angle amplitude getting smaller in the left-arm, the advantage switches at position 70° when object proximity and a reduction in joint amplitudes combine to favor the nondominant left-arm. Furthermore, we also found similar aspect at position 110° for left-handers. Therefore, a key feature of the limb switching phenomenon in our study seems to be more linked to a number of utilization of joints of the freely selected limb than to the times spent decelerating the limb.

Another key finding with regard to the limb switching phenomenon is the existence of a zone that gives an equal amount of kinematic advantages for both arms. As shown in Study 1, we found the same *Zero Zone* in the present study. As the target was moved away from the body midline, the free-arm started showing greater control efficiency than the forced-arm. In other words, the free-arm had significantly efficient kinematics for positions 50°, 60°, and 70° in left-hemisphere and for positions 110°, 120°, and 130° in right-hemisphere among right-handed participants. We found this *Zero Zone* in joint kinematics such as EA (80° to 90°) and the SA (80° and 90°). A similar aspect was also found in our left-handed participants. However, the *Zero Zone* of left-handers was somewhat different. Thus, the *Zero Zone* was shifted 10 degree more away from the body midline into right-hemisphere compared to the *Zero Zone* of right-handers. Thus, we found the *Zero Zone* of left-handers with similar kinematics such as EA (90° to 110°) and SA (90° to 100°). For these positions, we found no differences in joint kinematics between the free- and forced-arm. Therefore, our data defined the *Zero Zone* as positions of 80° and 90° for right-handed participants and as positions of 90°, 100°, and 110° for left-handed participants.

After applying the concept of the Zero Zone to our target positions, for right-handers, our nine target positions can be divided into three different zones: 1) a Nondominant Zone (50°, 60°, 70°), 2) a Zero Zone (80° and 90°), and a Dominant Zone (100°, 110°, 120°, 130°), whereas for left-handers our nine target positions can be divided into three zones: 1) a Dominant Zone (50°, 60°, 70°, 80°), 2) a Zero Zone (90°, 100°, 110°), and a Nondominant Zone (120°, 130°). The boundaries between the Nondominant Zone and the Zero Zone were consistent with the switchover points in limb selection for both handedness groups. The switchover point of left-handers was shifted 10 degrees more away from the body midline as compared to the one of right-handers. Also, the boundary between the Zero Zone and the Nondominant Zone of left-handers was shifted 10 degrees more away from the body midline as compared to the Zero Zone of right-handers. That is, the boundary of the Zero Zone into contralateral hemispace for right-handers was 10 degrees away from the body midline, whereas the boundary of the Zero Zone into contralateral hemispace for left-handers was 20 degrees away from the body midline. This 10 degree difference between right- and left-handers was exactly consistent with the switchover points of both handedness groups in the limb selection.

These findings are exactly consistent with the results of Study 1. Interestingly, however, when we analyzed joint kinematics separately as a function of speed, we found kinematic changes between the slow and the fast speed. That is, for the slow speed, the Zero Zones of our right-handed participants were positions of 80° and 90° for EA and positions of 80° and 90° for SA, which were identical with the overall results. Also, the Zero Zones of our left-handed participants for the slow speed were not different from the

overall Zero Zones. However, for the fast speed, the Zero Zones of both right- and left-handers were shifted 10 degrees more into nondominant contralateral hemispace as compared to the Zero Zones for the slow speed. That is, the Zero Zones of right-handers were position 70° to 100° for EA and position 70° to 90° for SA while the Zero Zones of left-handers were position 90° to 120° for EA and position 90° to 110° for SA. Thus, the Zero Zones for EA and SA extended 10 degrees into nondominant contralateral hemispace for both handedness groups when the fast target was presented. The boundaries of these extended Zero Zones are substantially consistent with the switchover points of both handedness groups when the fast target was presented.

We thus suggest that kinematic advantages with regard to joint utilization drive limb selection in the Nondominant Zone and the Dominant Zone. In other words, participants select their nondominant arm when kinematic advantages exist. On the other hand, when the kinematic advantages are equivalent for either hand (in the Zero Zone), it is plausible that there is no reason to select the nondominant-arm anymore, and instead the dominant-arm can be easily selected. We therefore conclude that kinematic advantages with regard to a reduction in degrees of freedom for limbs are the primary factor for the limb switching bias around 80° for right-handers and 110° for left-handers. With similar kinematic advantages (in the Zero Zone), motor dominance is the most influential factor for limb selection. In summation, kinematic advantages with regard to a reduction in the control of the reach from a two-joint to a single-joint movement seem to provide more adequate explanations for the limb selection phenomenon rather than the DDH.

*Dynamic Dominance Hypothesis*

In Study 2, we did not find evidence to support the left-arm advantage of controlling final position based on the accuracy (PE and DL) data. Rather, the dominant right-arm (right-handers) and nondominant right-arm (left-handers) had more accurate final position for contralateral movements. These results of the occurrence of the right-arm advantage among right- and left-handers are more consistent with the view that reflects specialization of the dominant arm/hemisphere for the visual-mediated correction process (Carson, 1989; Flowers, 1975; Roy & Elliott, 1989; Todor & Cisneros, 1985). With regard to the dominant right-arm advantage in the dynamic control of the hand-path trajectory, we predicted that the right arm/left hemisphere system would reveal greater performance in dynamic control of the hand-path trajectory for both of the handedness groups. For ipsilateral movements, however, we found no difference between limbs in hand path curvatures for both handedness groups. Instead, we found that the hand-path trajectory increased as the target was moved away from the body midline. For contralateral movements, the left-arm disadvantage was revealed among right- and left-handers when the target was moved away from the body midline, indicating that the right-arm advantage was revealed more clearly when requiring more coordination of multi-segment dynamics. These results of final position accuracy and hand-path curvature contradicted the DDH and are more consistent with the view that the dominant right-arm/left-hemisphere system shows superior performance in terms of speed, accuracy, consistency, and control over the nondominant arm (Annett, Annett, Hudson, & Turner, 1979; Flowers, 1975; Roy, 1983; Roy & Elliott, 1989; Todor & Doane, 1978; Woodworth, 1899).

With inverse dynamic analysis, we found different muscle torque utilization between the dominant and nondominant arms at each joint. That is, the dominant arm showed less elbow muscle and greater shoulder muscle torques for ipsilateral movements when the fast target was presented, indicating that the dominant arm had better utilization of joints for the fast speed in which inter-segmental dynamic effects were small. In other words, for positions of Farthest and Far which produce mainly single-joint (elbow) movements for both limbs, the dominant arm employed not only the elbow but also the shoulder for reaching. These different muscle torque strategies did indicate the dominant-arm advantage but did not indicate the right hand advantage difference because the dominant-arm data included both right-arm (for right-handers) and left-arm (for left-handers). After separate observation of the data as a function of handedness, we found that the dominant arm showed less elbow muscle (or greater interaction) and greater shoulder muscle torque than the nondominant arm for both right- and left-handers. Therefore, these findings are more consistent with the DDH rather than the right hand/left hemisphere advantage. However, we did not find these results for contralateral movements as well as for the slow target condition. Because of these inconsistencies in the dominant arm hypothesis (i.e. fast versus slow, ipsilateral versus contralateral), we are not able to support the DDH.

Rather, our data suggested that joint torques were highly related to a target position. That is, interaction torques and shoulder muscle torques decreased as target position moved away from the body midline, whereas elbow muscle torques increased as target position moved away from the body midline. These results indicated that a reduction in the

control of the reach from a two-joint (shoulder and elbow) to a single-joint (elbow) movement occurred as target position moved away from the body midline. Overall, the torque impulse for the dominant-arm movement, as compared to the nondominant-arm movements, did not reveal less elbow muscle torque at the elbow and greater elbow muscle torque at the shoulder. We also found no significant torque differences between elbows for each limb among left-handers. As a result, we hesitate to support the DDH that elbow muscle torque contributed essentially less toward the dominant right elbow movements.

In sum, our data are more consistent with the view that the dominant right-arm/left-hemisphere system shows superior performance in speed, accuracy, consistency, and control over the nondominant arm (Annett, Annett, Hudson, & Turner, 1979; Flowers, 1975; Roy, 1983; Roy & Elliott, 1989; Todor & Doane, 1978; Woodworth, 1899). Although we found similarity in the dominant arm advantage between the DDH and our data for ipsilateral movements, we do not know whether this similarity was from the DDH or from the more traditional view. Rather, the data of final position accuracy and hand-path trajectory revealed the right hand superiority even among left-handers. Therefore, our data are more consistent with the view that the right-arm/left-hemisphere system shows superior performance in speed, accuracy, consistency, and control over the left-arm/right-hemisphere (Annett, Annett, Hudson, & Turner, 1979; Flowers, 1975; Roy, 1983; Roy & Elliott, 1989; Todor & Doane, 1978; Woodworth, 1899).

## CHAPTER IV

### DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

#### General Discussion

This study was inspired by the work of Gabbard and colleagues (2001, 2003, 2004) that revealed limb selection changes from dominant-arm to nondominant-arm around an object position of 70° for right-handers and 110° for left-handers after passing the body midline (90°) into contralateral hemispace. The research questions for this study were posed to examine the generalization of the Dynamic Dominance Hypothesis (DDH) in regard to limb dominance, limb selection, and limb action. The presented studies asked the following questions: *can the DDH explain why people select their nondominant hand for reaching into their contralateral hemispace? (Limb selection) Do predictions of the DDH hold for right- and left-handers? (Limb dominance) Do propositions of the DDH apply to different reaching speeds? (Limb action)*

More specifically, the purpose of Study 1 was to investigate the relationship between limb selection and the DDH among both handedness groups. Thus, Study 1 addressed the following questions: *Can the DDH explain why people select their nondominant hand for reaching into their contralateral hemispace? Do predictions of the DDH hold for right- and left-handers?* Based on the DDH, we predicted that the dominant arm would show advantages of controlling limb dynamics, and the nondominant arm would reveal more accurate final positioning for both of the handedness groups. In limb selection analyses, we predicted that the selected limb would show faster movement times



and be more accurate with more contribution of interaction torque to limb motion than the unselected limb in both handedness groups. Furthermore, we also predicted that the transition point in limb selection between the two hands would correlate with the point where certain kinematic and kinetic variables were identical. The primary intent of Study 2 was to further investigate a generalization of the DDH for reaches of different speeds (slow and fast). Furthermore, this study examined whether a change in speed for reaching movements can influence limb selection. Therefore, we designed slow and fast reaching movements in order to increase task difficulty, as opposed to participant's elected natural speed in the previous studies. Based on the design of Study 2, we predicted that the right arm/left hemisphere system would reveal greater performance in dynamic control of the hand-path trajectory for both handedness groups. For both Study 1 and Study 2, reaching movements were made to each of nine targets using free-choice and forced-choice paradigms.

In regard to our initial question 1: *Can the DDH explain why people select their nondominant hand for reaching into their contralateral hemisphere? (Limb selection)* As one of the attempts to address the question, Stins et al., (2001) suggested that the point where participants switched from a dominant to a nondominant arm was associated with the point where the deceleration times of both hands were equal. This hypothesis implies that limb choice is related to limb kinematics. In our previous study, however, we found the similar switchover point where the deceleration times of both hands were equal in both right- and left-hemisphere, indicating a symmetric effect by joint utilization as contrasted with efficient feedback processing. Therefore, we concluded that limb selection was

related to advantages linked to a reduction in the control of reaching from a two-joint to a single-joint movement, rather than control efficiency with regard to the amount of time devoted to feedback processing that might occur in the deceleration phase of the reach. Moreover, the positions of  $80^\circ$  did not seem to be linked to any biomechanical limits (Kim et al. 2007). Furthermore, a recent selection study from our lab revealed that random and systematic target placement conditions did not influence limb selection preference among strong right-handed participants. In other words, the frequency of dominant right use in limb selection intersected consistently around the positions of  $80^\circ$  regardless of the three object positioning conditions, indicating the bias was not a function of previous limb selection. If the DDH can explain why people select their non-preferred (nondominant) hand instead of the preferred (dominant) hand, an increase of the non-preferred hand use must appear when accuracy demands are high because of the nondominant arm advantages of controlling end-point accuracy based on the DDH. However, in the present study, we did not find this change when our small or fast targets were presented. Also, the nondominant arm advantages of accurate limb position did not appear even when the non-preferred hand was dominantly used at positions far from the body midline. Rather, the preferred hand had more accurate final position. Therefore, the DDH is an inadequate explanation for the limb selection phenomenon. Instead, kinematic advantages with regard to a reduction in the degrees of freedom for limbs are the primary factor for the limb selection phenomenon. With similar kinematic advantages (in the Zero Zone), motor dominance is the next influential factor for limb selection. In summary, kinematic advantages with regard to a reduction in the control of reaching from a two-joint to a

single-joint movement seem to be a more fundamental cause for the limb selection phenomenon rather than the DDH. Also, our data reveal that kinematic differences between right- and left-handers with regard to the utilization of joints for reaching are related to limb selection characteristics between right- and left-handers.

With regard to question 2: *Do predictions of the DDH hold for right- and left-handers? (Limb dominance)* Basically, we did not find the distinct features of the DDH for either our right- or left-handers. In Study 1, we found that the dominant arm had even more accurate final position than the nondominant arm for right-handers, whereas there was no difference between limbs for left-handers. Also, we found that our right-handers had more accurate final position than our left-handers. In Study 2, the dominant right-arm (for right-handers) and the nondominant right-arm (for left-handers) had more accurate final position than the opposite hands. These results contradicted what would be expected based upon the DDH (which would predict differing results based on the postulate that arm advantages were the dominant factor.) With regard to the dominant right-arm advantage in dynamic control of the hand-path trajectory, as shown in the final position accuracy data, the dominant right-arm (right-handers) and the nondominant right-arm (left-handers) had even straighter hand-paths than the opposite hands. For ipsilateral movements, however, we found no difference between limbs in the hand path curvatures for both handedness groups. Instead, we found that the hand-path trajectory increased as the target was moved away from the body midline. For contralateral movements, the left-arm disadvantage was revealed among right- and left-handers when the target was moved away from the body midline, indicating that the right-arm advantage was revealed more clearly when requiring

more coordination of multi-segment dynamics. This result of the occurrence of the right-arm advantage among right- and left-handers suggests that handedness is substantially related to the view that reflects specialization of the right-arm/hemisphere for visually-mediated correction process (Carson, 1989; Flowers, 1975; Roy & Elliott, 1989; Todor & Cisneros, 1985). We did find that this right-arm/left-hemisphere advantage was revealed more clearly among right-handers rather than left-handers and that right-handers showed better performance in final position accuracy than left-handers. This finding suggests that our left-handed data were consistent with one important implication from the right arm/left hemisphere advantage hypothesis in visually guided reaching and aiming movements. That is, failure to develop right-hand preference might reflect a failure to optimize the visuomotor control. In other words, people who show left- or mixed-hand preference might be at a disadvantage for the performance of tasks that stress visuomotor coordination of multi-segment dynamics with the dominant arm (Grouios, 2006)

In regard to the question 3: *Does the DDH hold for a wide range of speeds? (Limb action)* Because left-handers had shorter total movement times than right-handers in Study 1, indicating that left-handers had disadvantage in visual-mediated correction process, we suspected that this contradiction to the DDH might result from different movement times between dominant- and nondominant-arm reaching. Therefore, in Study 2, we designed similar movement time for both limbs using a timing task. As generally expected by the design of the task, movement times of each limb corresponded exactly with speeds of the moving targets (fast: 550 ms vs. slow: 1500 ms). Even with the similar movement times, we still did not find the nondominant arm advantage of the DDH for both of the

handedness groups. With regard to the dominant arm advantage in controlling limb dynamics, we generally found no evidence to support the dominant arm advantage predicted by the DDH. The data of Study 1 were substantially different from the data of Study 2. In Study 2, we found the dominant arm advantage as compared to the nondominant arm only when the fast target was presented. However, there was no difference between limbs in Study 1 and Study 2 with the slow target. This inconsistency may be caused by different movement times of reaches between Study 1 and Study 2 as well as between the fast and slow targets. Study 1 and our slow target condition in Study 2 had enough time for both limbs to execute reaches with error correction through visual feedback processing. That is why no differences in the dominant arm advantages between limbs occur in Study 1 and the slow target condition in Study 2. Therefore, the nondominant arm advantages of controlling limb position as well as the dominant arm advantages of controlling trajectory were not revealed in our studies. Also, the dominant arm advantage shown in the fast condition in Study 2 could be significant evidence for the right-hand/left-hemisphere superiority rather than the DDH. In summary, our data indicate the DDH does not hold for either slow or fast speed in reaching movements. Rather, a change in kinematics with regard to utilization of joints in reaching movements is associated with movement speed.

The results from Study 1 and Study 2 combine to produce one of the most significant findings in these present studies. Specifically, there is close correlation between limb selection phenomenon and control efficiency. Both studies revealed that limb selection is highly associated with control efficiency (i.e. efficient joint utilization).

Interestingly, as we discussed earlier, kinematic changes due to a change in speed corresponded to limb selection changes due to a change in speed. That is, in Study 1, our target size (small vs. big) did not influence limb selection, and control efficiency did not show differences between the small and big targets. In contrast with respect to Study 2, our target speed (slow and fast) influenced limb selection and control efficiency between limbs due to the differences between the slow and fast targets. While our previous work addressed hand dominance, hemispheric bias, and object proximity as possible factors in limb selection, none of these views explained why the switchover points occurred around the position of  $80^\circ$  for right-handers and the position of  $100^\circ$  for left-handers. Therefore, our findings contradict the traditional view (limb dominance) as well as more contemporary views (hemispheric bias or object proximity) as possible explanations for the limb selection phenomenon. In contrast to the previous explanations for limb selection, the present set of studies demonstrates that control efficiency is the primary cause for limb selection. The broader question we address here is how people select, from all potential movements and control options, those that are most adaptive or suitable in terms of meeting the task's requirements, as mentioned in the study of Stins et al. Our interpretation for an answer is motivated by two perspectives. The first of those reflects the energetics of movements. That is, changes to the biomechanics of novel gross-motor tasks over trials have been observed in correlation with changes in metabolic energy cost (Sparrow, Hughes, Russell, & Le Rossignol, 2000; Sparrow & Newell, 1998; Todorov & Jordan, 2002). For example, in the studies of walking on hands and feet on a motor-driven treadmill, metabolic energy expenditure was shown to decline over trials when walking speed and

trial duration remained unchanged (Sparrow & Irizarry-Lopez, 1987; Sparrow & Newell, 1994). More recently, in a study using an ergometer rowing task, the metabolic energy cost decreased over trials when investigators fixed the task demands by maintaining a constant external power output (Lay, Sparrow, Hughes, & O'Dwyer, 2002; Sparrow, Hughes, Russell, & Le Rossignol, 1999). Although, in our studies, we did not directly measure metabolic energy cost, there is no doubt that less shoulder and elbow angle amplitudes indicate low energy cost compared to greater angle amplitudes. Also, a recent study supported this idea that the kinematics and metabolic costs are strongly correlated (Lay, Sparrow, & O'Dwyer, 2005). The second of those perspectives concerns the coordination dynamics or dynamic pattern approach (Kelso, Buchanan, & Murata, 1994). In particular, this idea has been found in that tradition of the cognitive or attentional energy of maintaining interlimb coordination patterns (Temprado, Zanone, Monno, & Laurent, 1999). There, two perspectives are related to each other but, until recently, they have been independent areas of research. In a recent study, Lay, Sparrow, and O'Dwyer (2005) measured not only attentional variables but also the metabolic energy cost of performing a high-energy, intrinsically unstable, 90° relative phase coordination pattern. That is, as the kinematic error of the target relative phase pattern decreased with practice, the metabolic energy cost and the attentional demand also reduced. This finding suggested a link between control efficiency and the metabolic and attentional costs of coordination.

Another key finding in the present studies is evidence for the right hand/left hemisphere advantage. With regard to limb differences in the control of reaching, the DDH is one of the most recognized contemporary theories and a widely accepted explanation for

limb difference. However, our data did not reveal evidence to support the DDH. Rather, our data are consistent with the right-hand superiority effect. To account for the superiority of the right arm, many attempts have focused on the processing characteristics of the contralateral or left cerebral hemisphere (Elliott & Chua, 1996). Three main hypotheses of the right hand advantage for reaching movements have emerged in the literature. The first proposes that the right-arm superiority is because of a more effective and consistent motor-programming capacity of the left hemisphere (Roy & Elliott, 1989; Carson, Chua, Elliott, & Goodman, 1990). Due to this advantage, the right arm shows less variability in the selection and specification of appropriate muscular forces (Annett et al., 1979) or greater precision of force modulation (Peters, 1981). The second hypothesis suggests that the right-arm advantage is based on a specific capacity of the left cerebral hemisphere to process visual feedback from the ongoing movement (Flower, 1975; Todor & Cisneros, 1985). In particular, the right hand is thought to be associated with a neural substrate, which may more effectively use sensory information (Flower, 1975; Todor & Doane, 1978). The last hypothesis indicates that the right hand has an advantage because right-handers distribute their attentional resources more directly toward the right hand when they perform goal-directed movements (Roy & Elliott, 1989; Helsen, Starker, Elliott, & Buekers, 1998). Thus, this assumption suggests that attentional biases are directed towards the right hand during tasks that require both hands to move simultaneously (Peters, 1981). Our data are more consistent with those hypotheses of the right hand advantage. First of all, our right- and left-handed participants showed more accurate final position and straighter hand-path for the right arm compared to the left arm, regardless of limb dominance. This



finding has led to the assumption that the right-hand/left-hemisphere advantages for the efficacy of visual-feedback corrections give accuracy advantages to the right hand. Also, our data reveal no difference in final position accuracy between limbs for left-handers, and this finding is consistent with one important prediction from the right hand advantage. That is, interlimb differences in movement accuracy tend to be reduced when movements are performed with shorter executing time, indicating a reduction in the role of visual-feedback corrections (Flowers, 1975). In other words, no difference in accuracy between limbs for left-hander implies that this prediction is true. Finally, we found that left-handers showed shorter movement times than right-handers, regardless of hand, target condition, and position. This finding is more consistent with a hypothesis, which reflects an attentional advantage of left hemisphere. Furthermore, results to support for the attentional explanation of limb differences were revealed in recent studies, which indicated that goal-directed movements are actually initiated more quickly with the left hand for right-handers because of distributing attentional resources more directly toward the right hand. As a result, our left-handers were able to produce relatively faster movements compared to right-handers.

Finally, in the quest to better understand the determinants of limb selection for reaching, our data support the *Energy-Minimization Hypothesis* as Sparrow and Newell (1998) proposed that in response to task-environment constraints, the emergent pattern of limb selection or limb coordination may be the one that minimizes demands on the organism's limited energy resources. With respect to limb difference and handedness in the

control of reaching, we agree to a view, the *Dominant Hemisphere Hypothesis* rather than a more contemporary view, the *Dynamic Dominance Hypothesis*.

## **Conclusions**

Based on the obtained results and limitations of this investigation, the following conclusions seem warranted:

1. *Can the DDH explain why people select their nondominant hand for reaching into their contralateral hemispace?* Similar hand preference profiles indicate that limb selection is a substantially identical phenomenon for right- and left-handers. That is, limb selection change from dominant-arm to nondominant-arm occurs around an object position of 80° for right-handers and 100° for left-handers after passing the body midline (90°). Our data suggest that limb selection corresponds to control efficiency associated with a reduction in the control of the reach from a two-joint to a single-joint movement. Therefore, control efficiency with regard to a reduction in degrees of freedom in reaching movements seems to be a more adequate explanation for limb selection phenomenon rather than the DDH. However, this finding does not discount earlier suggestions of an attentional (perceptual) effect related to object proximity from the performer.

2. *Do predictions of the DDH hold for right- and left-handers?* In the context of our task, we found no evidence to support the DDH either for right- or left-handers. That is, our data do not support the propositions that the dominant arm is specialized for controlling limb dynamics and that the nondominant arm is specialized for controlling final limb position. Rather, we found differences between right- and left-handers with regard to utilization of shoulder and elbow joints. That is, the free-arm of right-handers had no

advantage of utilization of the same joints compared to the forced-arm until position 80° into left-hemisphere from the body midline. On the other hand, the free-arm of left-handers had no advantage of utilization of shoulder and elbow joints compared to the forced-arm until position 100° into right-hemisphere from the body midline. Therefore, our findings suggest that kinematic differences between right- and left-handers with regard to utilization of joints in reaching movements seems to be a more reasonable explanation for limb dominance (handedness) rather than the DDH.

3. *Does the DDH hold for a wide range of movement speed?* Our data suggest that target speed is a more influential factor than target size in limb selection. A change in speed shifts the limb switchover point 10 degree further from the body midline. This shift in the switchover point alters limb kinematics (i.e. elbow and shoulder angle amplitude) and the kinematic changes are consistent with the limb selection profiles for both handedness groups. Even with different movement speeds, no differences in final position accuracy and limb dynamics occurred between the dominant- and nondominant-arm. Therefore, our data suggest that the DDH does not hold for either slow or fast speed in reaching movements. Rather, a change in kinematics with regard to utilization of joints in reaching movements seems to be more associated with limb action (speed) rather than the DDH.

4. Overall, our attempts to explore fundamental questions about the relationship between limb selection, limb dominance (handedness), limb action (speed) and the DDH reveal that control efficiency with regard to a reduction in degrees of freedom in reaching movements seems to be a more fundamental cause for the limb selection phenomenon

rather than the DDH. Also, our data reveal that kinematic differences between right- and left-handers with regard to utilization of joints for reaching explain limb dominance. Finally, our data suggest that a change in kinematics with regard to utilization of joints is highly associated with movement speed. In conclusion, our data indicate that the DDH is an inadequate explanation of differences in limb selection, limb dominance (handedness), and limb action (speed). Rather, our findings with regard to control efficiency seem to be more fundamental and justified explanations for limb differences in the control of the reach based on the context of our task.

### **Recommendations**

Although the present studies addressed several prominent questions, our conclusions were limited to some features. First, despite the fact that we found differences between our data and the DDH, there remains a possibility that participants in every trial did not thoroughly perform constant reaching movements from the start to the end. This study was also limited in the context of a reaching task used by our participants. Our reaching task was not identical to the movements Sainburg employed in his studies. Another limitation is that our experiments for investigating the DDH only examined an aspect of the DDH. That is, our studies pursued only the dominant and nondominant limb advantages, instead of interlimb differences in control of movement extent and interlimb transfer of motor learning. We did not examine those features of the DDH in the present studies, and thus we cannot comment generally with respect to those aspects of the DDH. Finally, our paradigm, due to its behavioral nature, could not depict the areas of the brain involved in the dominant and nondominant limb/hemispheric systems.

In regard to the extension of this work, future studies should investigate the extent to which original tasks, as shown in Sainburg's studies, might be employed and to which more various tasks such as bimanual tasks can be utilized in future studies. Another extension of this work is to test the rest of the DDH features. That is, we did not investigate interlimb differences in control of movement extent and interlimb transfer of motor learning. Therefore, it is worthwhile to examine various distant reaching movements through learning procedures. If we find additional evidence to support the DDH through various tasks, it could be a hint toward understanding the differences we found in the present studies and would also allow a reexamination of the present conclusions.

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