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SENSORIMOTOR PERFORMANCE ASYMMETRIES AND HAND PREFERENCE

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JUNE 2011

SENSORIMOTOR PERFORMANCE ASYMMETRIES AND HAND PREFERENCE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF SOCIAL SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

SELÇUK AKPINAR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF PHYSICAL EDUCATION AND SPORTS

JUNE 2011

Approval of the Graduate School of Social Sciences

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ABSTRACT

SENSORIMOTOR PERFORMANCE ASYMMETRIES AND HAND PREFERENCE

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June 2011, 159 pages

This dissertation presents three experiments to investigate the general distribution of hand preference across a reachable working space, as well as the effect of sensory information about the reaching hand, and if this distribution is affected by long term practice. In addition, the underlying mechanisms of hand preference behavior were investigated with the obtained kinematic data.

Experiment 1 explored the distribution of hand preferences across the workspace among non-athlete right-handed participants, as well as the role that visual feedback might play in this distribution. Experiment 2 tested the hypothesis, if occlusion of visual feedback influences hand preference, accordingly interlimb differences. The third final experiment examined the effect of long term practice on hand preference among right-handed elite fencers.

The first study showed that the choice of arms is related to the energetic cost and dynamic efficiency of the movements. The results of the second experiment displayed that the choice of hands changes under no visual feedback condition, demonstrating that the choice is active and not habitual, depending on sensorimotor performance asymmetries. The final experiment demonstrated that elite athletes have different patterns of limb selection than non- athletes. Athletes, specifically fencers, show improved coordination in their non-dominant arms, which apparently increases the selection of this arm for reaching. Overall, it was concluded that hand preference depends on sensorimotor performance asymmetries and influenced by the long term practice.

Key words: Hand Preference, Interlimb Differences, Sensory Information, Fencers, Non-athletes.

ÖZ

SENSORİMOTOR PERFORMANS ASİMETRİSİ VE EL TERCİHİ

Akpınar, Selçuk
Doktora, Beden Eğitimi ve Spor Bölümü
Tez Yöneticisi : Yrd. Doç. Dr. Sadettin KİRAZCI

Haziran 2011, 159 sayfa

Bu tez kapsamında üç farklı deney yapılmış ve bu deneylerde kişilerinin uzanma gerektiren hareketlerde el tercihinin nasıl bir dağılım gösterdiğine bakılmıştır. Bunun yanında uzanma hareketi sırasında el ile ilgili görsel bilginini olup olmaması ve uzun süreli yapılan egzersizlerin el tercihini nasıl etkilediğine bakılmıştır. Son olarak da, el tercihine etki eden faktörlerin neler olabileceği araştırılmıştır.

Yapılan birinci deneyde sporcu olmayan kişilerde elleri ile ilgili görsel bilgi varken el tercihlerinin dağılımına bakılmıştır. İkinci deneyde, yine sporcu olmayan kişilerde elleri ile ilgili görsel bilgi olmadığı durumlarda el tercihi dağılımına bakılmıştır. Son deneyde ise, eskrim sporcularında uzun süreli yapılan egzersizin el tercihine olan etkisi araştırılmıştır.

İlk deneyin sonuçları el tercihinin uzanma hareketi için harcanan enerji ve dinamik olarak ne kadar etkili yapıldığı ile ilişkili olduğunu göstermiştir. İkinci deneyde, uzanılan el ile ilgili görsel bilgi olmadığında el tercihinin değiştiği ve bu değişimin ilk deneyde olduğu gibi hareket için harcanan enerji ve ne kadar etkili yapıldığı ile ilişkili olduğu bulunmuştur. Dolayısıyla el tercihinin aktif bir karar olduğu söylenebilir. Yapılan son deneyde ise, eskrim sporcularının sporcu olmayanlara göre el tercihlerinde farklılık olduğu bulunmuştur. Eskrim sporcularında baskın olmayan sol elin gelişimi sporcu olmayanlara göre daha iyi olduğu için, sporcular sol ellerini sporcu olamayanlara göre daha fazla tercih etmişlerdir. Sonuç olarak, el tercihi eller arasındaki sensori motor performans farklılıklarını bağlıdır ve uzun süreli egzersizden etkilenmektedir.

Key words: El Tercihi, Ellerarası Farklılık, Sporcular, Sporcu Olmayanlar.

To My Family

ACKNOWLEDGEMENTS

First, I’d like to thank Assist. Prof. Sadettin Kirazcı, my PhD thesis advisor. He was my graduate supervisor throughout all my years at METU. Next, I’d like to thank my committee members: Prof. Gazanfer Doğu, Prof. Robert L. Sainburg, Prof. Feza Korkusuz, and Assist. Prof. Serdar Arıtan. Thank you for your insight and advice throughout the PhD defense process.

I owe a debt of gratitude to Prof. Robert L. Sainburg and his lab members for their contributions to experiments in this dissertation; Dr. Andrzej Przybyla, Dr. Pratik Mutha, Tucker Tomlinson, and Chase Coelho. Prof Sainburg accepted me as a visiting scholar and inspired me to do these experiments. Dr. Przybyla spent many hours to teach me how to use the experimental setup, Kinereach. PhD students, Tucker and Chase, helped me a lot for testing process and contributions. I would not have been able to complete this thesis without their helps. Thank you very much for all your time and effort, it is deeply appreciated!

I’d like to thank my dear friends, B. Okan Miçooğulları, Bilal Biçer, Emre Ak, Mehmet Uygur, Dr. Özge Uygur, Ahmet Yıldırım and all people in my department at METU. They always supported me throughout my PhD education. Special thanks also to Prof. Hülya Gökmen, Muhsin Gökmen and Dr. Tayfun Gökmen who encouraged me to come to METU.

To my family – my mom Emine, dad Memet, sisters Sibel and Mevlüde, and brother Şahin. You have always been there for me and supported me through the most difficult times.

Last but certainly not least, to my wife Aysun and son Burak. No one has done more to get me through this stage than you. You have been my constant support. Thank you from the bottom of my heart.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Approximately 90% of the population is right-handed (Caliskan & Dane, 2009; Jung & Jung, 2009; Perelle & Ehrman, 1994; Vuoksimaa, Koskenvuo, Rose & Kaprio, 2009) and prefer to use the dominant hand for dynamic activities such as throwing or cutting. Most activities of daily living, including brushing one's teeth, combing one's hair, or flipping a light switch, can be performed automatically without conscious effort. When such activities only require a single hand, one may choose either non-dominant or dominant hand, depending on task requirements. Some tasks that require two hands, like peeling a banana or cutting bread, distribute different task requirements between the hands. We often perform holding task with the non-dominant hand, and the movement task with the dominant hand. Even though we often view hand dominance, or "handedness" as reflecting different proficiencies of our two arms, handedness is commonly assessed by questionnaires about preferences, rather than by measuring differences in performance. Hence, the terms "handedness" and hand preference" have been used interchangeably in the literature, which may often be a misnomer. Nevertheless, the relationship between interlimb differences in movement performance and limb choice is not well understood. We suggest that if the accuracy or efficiency of performance is not a factor, one should be able to use either hand, equally well.Factors other than movement proficiency, such as proximity of the hand to the task are playing a larger role in choosing the hand to use. However, when a task requires skillful manipulation, such as targeted throwing, the choice is not equivocal. The factors that determine the choice of which hand to use for a given task should provide insight into the mechanisms that underlie handedness.

Hand preference is generally assumed an invariant biologically based trait. However, many studies stated that other factors such as object location and attentional information related to task demands can also influence that phenomenon (Gabbard, Tapia, & Helbig, 2003; Gabbard, Rabb, & Gentry, 1998; Gabbard & Helbig, 2004; Gabbard & Rabb, 2000; Leconte & Fagard, 2006; Mamolo, Roy, Bryden, & Rohr, 2004). The results of these studies reveal that task and context play an important role in the process of hand selection. Task dependency was previously shown in experiments where decreasing tools' sizes (Bryden, 1999) or reaching and picking up full glasses in comparison to the empty ones (Stins, Kadar, & Costall, 2001) led to increase in the right hand bias. Furthermore, Gabbard and Helbig (2004) showed analogous behavior when subjects were asked to pick up an object in either left or right hemispace and transport it across the workspace to the opposite hemispace. In general, these studies attributed hand selection bias to the task demands. When the task dependency is minimized if not eliminated, the right hand selection bias has been attributed to hand preference.

In order to explain the possible factors of hand selection for reaching tasks, researchers have noticed that strongly lateralized right-handers use their dominant hand to cover approximately 60% of the frontal space in the case of reaching movements (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003). Thus the midline of reaching frequency is skewed to the left by approximately

20 deg in reference to the midline of the body. The downside of these studies was a limitation to only 7 or 9 targets positioned in the arc design distanced at approximately 70% of arm length thus the space closer to the body was not explored. More recently, first attempts were made to explain the underlying mechanisms of such patterns of hand selection for reaching. Kim et al. (2007) examined the underlying kinematics of reaching movements and reasoned the cause of hand selection to the efficient joint torques strategies. Although this reasoning was not supported directly with the data, authors referred these ideas to the previous work of Sainburg et al. on the *Dynamic Dominance Hypothesis* (Sainburg, 2002; Sainburg & Kalakanis, 2000).

The *Dynamic Dominance Hypothesis* implies lateralization of brain functions in movement neurocontrol mechanisms. This hypothesis detailed motor performance asymmetries suggesting that each hemisphere/limb system is specialized for controlling different aspects of task performance. This hypothesis was termed, *Dynamic Dominance*, because of supports suggesting that the dominant arm has advantages in adapting novel dynamic conditions (Duff & Sainburg 2002; Sainburg 2002; Wang & Sainburg 2004), in specifying torque amplitude (Sainburg & Schaefer 2004), and in coordinating intersegmental dynamics during reaching (Sainburg & Kalakanis 2000; Bagesteiro & Sainburg 2002; Shabbott & Sainburg 2008). However, non-dominant arm often performs better with respect to final position accuracy without considering errors in coordination during the movement (Duff & Sainburg 2006; Wang & Sainburg 2007; Schabowsky, Hidler, & Lum 2007). According to this hypothesis, therefore, non-dominant hemisphere is specialized for control of steady state limb position, and dominant hemisphere is specialized for control of movement trajectory during reaching. These asymmetries in sensorimotor performance likely give rise to handedness.

As stated above, it was previously pointed out that in movements that were matched for speed, direction and displacement, the dominant arm use significantly less muscle torque than the non-dominant arm (Bagesterio & Sainburg, 2002; Sainburg & Kalakanis, 2000). Thus, these results emphasize using less efficient movement dynamics for the non-dominant limb. Other research has suggested that performance differences might also be related to asymmetries in visual or proprioceptive processing (Goble & Brown, 2007; Goble & Brown 2008; Goble & Brown, 2010). Goble and Brown (2008) have found non-dominant hand advantage during proprioceptive target matching but dominant hand advantage during visually determined target matching. In another study, Lenhard and Hoffmann (2007) have found that left hand performance was better for the final position accuracy during unimanual aiming task without visual feedback. Moreover, it has been proposed that hand preferences can be influenced through intensive practical training (Mikheev, Mohr, Afanasiev, Landis, & Thut, 2002). It has been reported that long-term participation of sport activities or musical practice can change motor preferences as well as the cortical representations of different body parts (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Mikheev et al., 2002). More specifically, one would expect that lateralization profiles in athletes should be associated with more right-hemispheric involvement as a result of over-training. Therefore, elite athletic performance should alter movement proficiencies with both hands. We predict that the pattern of hand selection in elite athletes should be different, as a group, than that of non-athletes.

The results of these studies give rise to idea that sensory information related to the task and long-term patterns of practice can play an important role on task performance. Therefore, in this dissertation, we conducted 3 experiments to ask, “Whether limb selection is, in fact, based on sensorimotor performance asymmetries and influenced by the long term patterns of practice".

1.2 Rationale of the Study

Studies aimed to find the possible factors of hand selection for reaching tasks are limited with the qualitative explanations (Gabbard et al., 2003, Gabbard & Helbig, 2004; Gabbard & Rab, 2000; Leconte & Fagard, 2006; Mamolo, Roy, Bryden, & Rohr, 2004). There is only one study investigated the underlying mechanisms of kinematic patterns of hand selection for reaching (Kim et al., 2007). They reasoned the cause of hand selection may be due to more efficient joint torques strategies which were found in earlier work of Sainburg and Kalakanis (2000).

In hand preference studies, there was a limitation to have only 7 or 9 targets positioned in the arc design distanced at approximately 70% of arm length. In this design, the space closer to the body was not explored. Thus, having targets closer to the body will provide additional information to hand preference literature.

Previous research has demonstrated that movements made without visual feedback are less efficiently coordinated than those made with visual feedback (Goble & Brown, 2008; Bagesterio & Sainburg, 2002). This suggests that sensory information can influence task performance during reaching movement which may also cause some changes in limb selection. Moreover, it is plausible to propose that long-term training should affect task performance and this performance may affect limb selection pattern in elite athletes. However, there is no study indicating neither the effect of sensory information nor the effect of extensive training on limb selection. Thus, the experiments in this dissertation would explain these phenomena with the quantitative data and get better understanding to underlying mechanisms of limb selection.

1.3 Research Questions

1. What is the distribution of left and right hand usage in the reachable working space?
2. Whether this distribution is affected by (a) Accuracy, Final Position Error (FPE) (b) Movement Quality, Hand Path Linearity (HPL) (c) Energetic Efficiency, Combined Joint Work (CJW)?
3. What is the effect of visual and proprioceptive feedback on distribution of hand usage?
4. What is the effect of long-term practice on this distribution?

1.4 Purpose of the Study

We aimed to find the distribution of left and right hand usage in a reaching task among non-athletes and athletes. Furthermore, we tried to investigate the effect of sensory information about the moving hand on hand selection and possible explanations for this distribution considering the kinematic data.

1.5 Research Hypotheses

1. Based on the previous findings, right hand reaching frequency will be more than that of left hand.
2. There will be a significant effect of sensory information on hand preference.
3. There will be a significant difference in hand preference among non-athletes and athletes.
4. Left and right hands will be significantly different in terms of FPE, HPL, and CJW during the reaching movements.

1.6 Delimitations

1. Participants consisted of 18-34 years old female and male non-athletes and athletes.
2. Athlete group was limited to elite fencers.
3. Right handed participants were included in this study.
4. For the non-athletes, hand preference was tested under two conditions (visual information and no-visual information during reaching movements).
5. For fencers, hand preference was tested only under visual information during reaching movements.

1.7 Limitations

1. Subjects of this study were not selected randomly.
2. Participants were limited to undergraduate and graduate students at the Pennsylvania State University.
3. Virtual Reality Environment (Kinereach) was used for the experimental set-up and was implemented in the laboratory situation.

1.8 Assumptions

1. The subjects gave their best effort during the experiments.
2. The subjects participated to the experiments at fully recovered state.

1.9 Definition and Abbreviation of Terms

The followings are definitions of terms that were operationally defined throughout this dissertation.

Final Position Error (FPE): It was defined as the shortest distance between the final positions of the cursor (index finger) and the center of the targets. It was taken as an indicator of accuracy.

Hand Path Linearity (HPL): It was defined as the ratio minor/major axis with the major axis being the furthest distance between any two points on the hand path and the minor axis being the furthest distance perpendicular to the major axis from any given point on the hand path. It was taken as an indicator of movement quality.

Combined Joint Work (CJW): It is the energy performed by muscles to accelerate/decelerate arm segments. It was taken as an indicator of movement efficiency.

Functional Magnetic Resonance Imaging (fMRI): It is a type of specialized scan that measures the hemodynamic response (change in blood flow) related to neural activity in the brain or spinal cord of humans or other animals.

Transcranial Magnetic Stimulation (TMS): It is a noninvasive method to cause depolarization in the neurons of the brain.

CHAPTER 2

LITERATURE REVIEW

For the experiments in this dissertation, we investigated the factors that might contribute to hand choice, using a choice paradigm in a reaching task in which targets were distributed across a large range of the available horizontal plane workspace.

This dissertation presents three experiments to address these questions: Experiment 1 explored the distribution of hand preferences across the workspace among non-athlete right-handed participants, as well as the role that visual feedback might play in this distribution. Experiment 2 investigated the effect of sensory motor information on the distribution of hand preference among non-athlete right-handed participants. Finally, experiment 3 examined the effect of long-term practice on the distribution of hand preferences.

This chapter gives basic information about the handedness, asymmetries causing this handedness, and studies related to the hand preference. In this part, literature about (1) Handedness, (2) Measurement of Handedness, (3) Origin of Handedness, (4) Anatomical Correlates of Handedness, (5) The Dynamic Dominance Hypothesis of Motor Lateralization, (6) Reaching Experiments with Hand Preference will be mentioned.

2.1 *Handedness*

While on gross inspection, the human body appears anatomically symmetric, asymmetry is a basic organizing principle of the human nervous system (Gazzaniga, 1989). Anatomical asymmetries in the hands (Hardyck & Petrinovich, 1977), feet (Brown & Taylor, 1988), eyes (Bourassa, McManus, & Bryden, 1996; Hebbal & Mysorekar, 2003) and ears (Hebbal & Mysorekar, 2003; Jung & Jung, 2003) are generally small. However, functional asymmetries in the nervous system can result in substantial behavioral asymmetries, including human handedness.

There is little doubt that handedness reflects asymmetries in neural function, rather than anatomical asymmetries in the arms and hands. However, a little is currently known about the neural mechanisms that give rise to handedness. In fact, there is controversy about how to define handedness. Some describe it has a preference for using one or the other hand for specific tasks, such as writing (Oldfield, 1971), while others suggest that the main characteristic of handedness is a difference in performance characteristics between the two limbs (Goble & Brown, 2008; Sainburg, 2002).

It well established that most humans are right-handed, and that the incidence of left- or right-handedness can vary slightly across different cultures (Perelle & Ehrman, 2005). According to cross cultural statistical studies, approximately 88 to 95% of the population from different countries and cultures is right-handed and prefer to use the dominant hand for activities such as throwing or writing (Caliskan & Dane, 2009; Jung & Jung, 2009; Perelle & Ehrman, 1994; Vuoksimaa, Koskenvuo, Rose, & Kaprio, 2009). Singh and Bryden (1994) reported differences in handedness between Canadians and Indians. Those two countries were expected to have very different distribution of handedness because of differences in social pressures to use right hand, which were higher in India. The rate of right-handedness was found to be 90.2% in Canada and 94.8% in India. Similarly, the rate of handedness in Japan, where social pressures are also higher, was shown to be higher than that of Canada (Ida & Bryden, 1996). McManus (2009) used a meta-analysis to draw a map, comparing the distribution of handedness between regions of the USA and many European countries. The variation in handedness across the selected regions changed only about 5%.

Considering the discrepancy of methods used for assessment of handedness or type of criterion used for categorization of handedness, it is generally thought that about 90% of the general population is right-handed (Previc & Saucedo, 1992). Surprisingly, this proportion of right-handed people has remained stable across geographical locations and cultures (Goble & Brown, 2008). Similar to human right hand bias, chimpanzees and other animals often prefer to use one hand or paw for particular actions (Bradshaw & Rogers, 1993). For instance, the work of Hopkins and Leavens (1998) has shown that adult chimpanzees significantly gestured with their right hand than with their left hand which shows the evidence for lateralization and right hand bias among chimpanzees. Thus, both humans and some animals show a strong preference for the right hand for several actions. In fact, this right hand bias for humans has maintained over the course of time by most of the population. Markers of hand preference in prehistory are found in material culture from the actions of lateralized tool manufacture and use that leave traces on objects, and in fossil skeletal asymmetries resulting from asymmetric use of the upper limb muscles over an individual’s lifetime (Uomini, 2009). For example, Latimer and Lowrance (1965) conducted a research on the weights and lengths of the right and left bones of each pair from 105 human skeletons from Asia. In general, they found that all of the long bones of the upper extremity were heavier and longer on the right side. The left bones were more variable in weight and length. The upper extremity and its bones noticeably had more asymmetry than the lower (Hebbal & Mysorekar, 2003). For the past 5000 years the best historical data are the study by Coren and Porac (1977), which looked at five millennia of artistic representations of unimanual motor activities (such as playing board games, throwing spears, writing, etc.). Overall about 92% of paintings, drawing, and sculptures show the right hand being used, with little variation over the entire period of recorded history. Thus, even in ancient cultures, humans were predominantly right handed.

2.2 Measurement of Handedness

Because handedness does not have a precise definition, nor is it understood from a mechanistic perspective, measurement of handedness is not standardized, and many different measures have been employed. It has been argued that both the direction (left or right) and the degree of handedness should be characterized when measuring handedness (Mamolo, 2008). McManus and Bryden (1992) also differentiated between performance and preference when measuring handedness. Preference refers to the hand that people select, when given a choice for a given task. Alternative, one can measure performance parameters, and characterize differences in movement accuracy, precision, movement time, or smoothness across the arms. This is an important distinction, because people can choose to use an arm that is not as skilled at performing the task. In fact, it is difficult to interpret a correlation between preference and performance, because preferences may produce changes in performance due to practice, and asymmetries in performance may also modify preferences (McManus, Murray, Doyle, & Baron-Cohen, 1992).

Self-report questionnaires are the most common tool to assess hand preference. Because it is very easy and quick to hand out questionnaires, they are one of the most popular methods of measuring handedness in both direction and degree (Bishop, Ross, Daniels & Bright, 1996). In some studies, they assessed handedness by observing the subjects' preference in performing an unskilled task (Plato, Fox & Garruto, 1984). One of the earliest questionnaires used to assess hand preferences developed by Annett (1970) Annett prepared a 12-item questionnaire that examined a variety of different tasks (such as throwing, using a racket, striking a match, etc.). The Annett handedness questionnaire could determine the strength of hand preference by examining those 12 tasks that the subjects reported doing with their preferred hand. One year later, the Edinburgh Handedness Inventory was published by Oldfield (1971). This inventory has 10 items and asks subjects to indicate the hand they would use to do those 10 activities, such as writing, throwing, striking a match, using a broom, etc. The instruction of this inventory states that participants can check both left and right hand usage if they have no preference. Dragovic (2004) in his study applied confirmatory factor analysis to test if this inventory is valid measure of hand preference. The result showed that most of the items of the Edinburgh Handedness Inventory were sufficient to provide an internally consistent and valid measure of hand preference. Comparing the 12-item Annett questionnaire and the 10-item Edinburgh inventory indicates that six of the items are the same in both questionnaires. It should be stressed that the constellation of tasks in the questionnaire as a whole might influence the way in which the identical items are answered (Williams, 1991). In general, the Edinburgh Handedness Inventory is by far the most commonly used assessment of hand preference for human research (Bishop, 1996; Seddon & McManus, 1993).

2.3 Origin of Handedness

As highlighted above, handedness has been studied for years and many theories of the origin of handedness have been proposed, however, answer for the "what determines handedness" is not clearly known. The list of factors that has been proposed to explain handedness is very large. For instance, some researchers attributed left-handedness with pathological disorders. Pathological left-handedness hypothesis has gained some support with higher frequency of left-handedness in schizophrenic patients and after childhood meningitis (Dragovic & Hammond, 2005; Ramadhani, Koomen, Grobbee, van Donselaar, Marceline van Furth, & Uiterwaal, 2006; Satz & Green, 1999). Besides this, a study showed that the rate of left-handedness was two times more common in infants who had required resuscitation after delivery (Williams, Buss, & Eskenazi, 1992). However, in contrast to Williams et al. study, Bailey and McKeever (2004) stated that only maternal age had a weak association with left-handedness. Moreover, result of some studies did not show a shift towards using left hand more frequently in schizophrenic patients (Malesu, Cannon, Jones, McKenzie, Gilvarry, Rifkin, Toone, & Murray, 1996: Taylor & Amir, 1995) so that pathological left-handedness hypothesis was not supported.

Some researchers have attempted to explain the determinants of handedness with looking at the handedness prevalence in singletons, twins, and triplets. Even though in a recent study of large number of twins and their siblings, Medland and his colleagues (2003) found no difference in left handedness between twins and singleton sibs (Medland, Wright, Gaffen, Hay, Levy, Martin, & Duffy, 2003), many studies found increased left-handedness in twins and triplets compared to singletons (Sicotte, Woods & Mazziotta, 1999; Vuoksimaa, Koskenvuo, Rose, & Kaprio, 2009; Williams, Buss & Eskanazi, 1992). Some speculate that the higher incidence of left-handedness in twins could be the smaller birth weight in twins than singletons and more stressful pregnancy and traumatic delivery (Sicotte, Woods, & Mazziotta, 1999; Vuoksimaa et al., 2009). As the gestation is the main determinants of birth weight in twins, they are born about 1 kg lighter at birth than singletons. Therefore, observed difference in prevalence of left-handedness between twins and singletons might partially have arisen from the lower average birth weight in twins. However, there is no much clear evidence and support for this idea and association between handedness and birth weight was found weaker (Medland et al., 2003). The controversial results in the literature also leave a question about the prevalence of handedness in twins. Besides, even if we think that stressful and traumatic pregnancy can account for some left-handedness, not all left-handedness does have a pathological origin (Vuoksimaa et al., 2009).

Additionally, it can be speculated as well that the typical uterine position of a fetus during the end of pregnancy can also be caused by the earlier formation of handedness. Many studies have observed handedness postnatally, but some ultrasound studies propose that the formation of handedness takes place prenatally. Researchers found right hand preference, in the form of thumb sucking, in fetuses at 10 weeks gestational age (Hepper, McCartney, & Shannon, 1998). Prenatal thumb sucking has also been found to be related to postnatal handedness at age 10 – 12 (Hepper, Wells, & Lynch, 2005). Thus, these ultrasound studies emphases the early formation of human handedness.

Helper and Coren (1988) emphasized the relationship between handedness and the age of subjects. They hypothesized that left-handers die at an earlier age than right-handers, and have a greater number of accidents. This hypothesis is controversial and there are some criticisms about the methodology, and failures to replicate empirical claims (Seddon & McManus, 1993). On the other hand, there are general agreements that the incidence of handedness seems to decrease with age and have increased in recent years (Strang, 1991; McManus, 2009).

There are mainly two common genetic theories which are based on Mendelian genetics. According to the Mendelian genetics, there is a set of primary tenets relating to the transmission of hereditary characteristics from parent organisms to their offspring; and this model underlies much of genetics. This model was initially derived from the work of Gregor Mendel (1865). He proposed two factors of heredity units, one of which is a recessive characteristic and the other dominant. Mendel stated that each individual has two factors for each trait, one from each parent. If the two factors are identical, the individual is called homozygous for the trait and if not, the individual is called heterozygous. The alternative forms of a factor are called alleges. An individual's physical appearance, or phenotype, is determined by its alleles as well as by its environment. The first theory that explains the genetic formation of handedness is Annet's right shift theory (RS). Annet in her book (2002), Handedness and Brain Asymmetry, stated that human handedness is similar to that of other primates and mammals in all except for one key respect. The essentials of the argument are that asymmetries depend on accidental differences between the sides that arise during early growth in bilaterally symmetrical organisms. The factor that is specific to humans weights the accidental chances in favor of right-handedness. The presence of the RS factor does not specify right-handedness, but put the probability towards that direction. This model proposes a single gene with two alleles (RS+ / RS-). RS+ has a strong liability to right-handedness, while RS- homozygote lacks a liability to either side and accordingly has a greater probability to be left-handed.

The other well-known genetic model of handedness is McManus model (McManus, 2004). Similar to Annet's model, this model suggest that at a single genetic location there are two alleles, named *D* (for dextral) and *C* (for chance). One hundred percent of *DD* homozgotes are right-handed, while *CC* homozygotes have a 50:50 chance of being either right- or left-handed. The alleles are additive in the heterozygote, so that 25% of *DC* individuals are left-handed, and the remaining 75% are right-handed.

Those models are not directly related to left- versus right-handedness; instead, they mainly determine whether there is a liability to right-handedness or no liability to either side.

Even though there is a familial aggregation of left-handedness, these genetic theories are inadequate to explain the formation of handedness (Vuoksimaa et al., 2009). These theories were proposed based on the Mendelian model but a study with a high number of samples showed that 76% of right-handed and 61% of left-handed subjects had no left-handed first degree relatives (Perelle & Ehrman, 1994). McManus and Bryden (1992) also reported that the prevalence of left-handed offspring was about 26% given two left-handed parents, about 20% given one right-handed and one left-handed parent, and about 10% given two right-handed parents. Furthermore, there are also two more criticisms of those models. First, there has been no study, which shows gene or genes responsible for implementing right hand tendency. Second, the numbers of pairs where one twin is left-handed and the other right is about 20-30% in spate of the fact that they have 100% overlap genetic characteristics.

While those genetic models have tried to predict the distribution of handedness, the genetic evidence for handedness largely hypothetical. However, Francks et al. (2007) recently made a claim to have identified the first potential genetic influence of human handedness. They have found a gene, LRRTM1 (Leucine-rich repeat transmembrane neuronal 1), that increases the likeliness of being left-handed (Francks et al., 2007). Even though this is the first concrete evidence for a genetic determinant of handedness, this claim gained a critic on the basis that the authors have made unjustified assumptions concerning mode of transmission both of psychosis and relative hand skill that they have failed to establish a parent of origin effect (Crow, Close, Dagnall, & Priddle, 2007). Thus, the origin of handedness is unlikely to be resolved.

The world is made up for the right-handed people. According to the theory which was proposed by Porac and Coren (1981), the general physical environment is in favor of the right-handers. Almost up to 98% of the equipments in every society are designed for right handed people. Examples for those equipments can vary from simple kitchen tools like can openers and utensils to very technological devices like camcorders and cameras. Moreover, left-handers have so many inconveniences in everyday facilities geared for the right-handers: handle position and opening/shutting direction of doors, key holes, position of cash and vending machines buttons, car engine keyholes, gearshift sticks, etc. Because most of those devices are made for right-handers, left-handers have to twist his or her left arm or switch to his or her non-dominant right arm in an unnatural way. We can also hear an offer by our left-handed friend at the table during lunch to sit at the far left end so that he or she will be comfortable during the meal.

There is also some suggestion that handedness may sometimes be the result of socio-cultural and environmental factors. In fact, there are some reports stating that relatively large numbers of adult left-handers have experienced attempts to switch writing hand to the right side (Porac & Searleman, 2002; Porac & Martin, 2007; Searleman & Porac, 2001). Moreover, Perelle and Ehrman (1994) also stated that parents discourage their children to use their right hand in one of the East Asian culture. However, it is very difficult to change hand preference especially at an early age. Indeed, most attempts to change handedness fail, and the process is bound to be difficult, or motor performance skill performance remains worse than originally preferred hand. Overall, although the determinants of human handedness are not clearly known, it seems most likely that both nature (genetics) and nurture (environment) play a considerable role and make a good combination to explain handedness.

After the discoveries of Broca in 1861 and Wernicke in 1874, the left hemisphere of right-handed people has long been known to be dominant for various aspects of language function (Goble & Brown, 2008). In 1908, Liepmann suggested that asymmetries in motor behavior might be related to the hemispheric processing differences. Liepmann hypothesized that the hemisphere contralateral to the preferred hand (i.e. left hemisphere for right-handed people) had a privileged role for both preferred and non-preferred hand during the control of voluntary movements. He had many ideas on cerebral localization of psychological function and conducted many studies on apraxia. Limb apraxia represents impairment in the ability to produce learned, skilled movements that is not attributable to primary motor or sensory loss, and is often caused by stroke, and has long been associated with left hemisphere damage. Liepmann conducted a study on hemiplegic right-handed patients. Hemiplegia is a condition in which the limbs on one side of the body have severe weakness.

In his study, the patients had either a right hemiplegia (indicating left hemisphere damage) or left hemiplegia (indicating right hemisphere damage) and tested on pantomime, imitation, and tool use. About 50% of the patients with a right hemiplegia had apraxic deficits, whereas none of the patients with a left hemiplegia exhibited such deficits. Liepmann found that apraxia was mostly associated with left hemisphere damage because there was no deficit in patients with right hemisphere damage. Furthermore, left hemisphere damage resulted in an inability to make skill movements with both hands, whereas only left hand was affected in right hemisphere damage. These results led Liepmann to conclude that left hemisphere of right-handed people played an enhanced role in the production of skilled movement (Mamolo, 2008).

It has been over 100 years after Hugo Liepmann idea about the dominant role of the left hemisphere of right-handed people. While this idea has gained support on a number of studies, more recent evidence shows that patients with right hemisphere damage can exhibit apraxic deficits as well. This study was conducted by Roy, Black, Blair, and Dimeck (1998). Roy et al. examined the gestural performance of 63 stroke patients with left or right hemisphere damage. They found that 54% of patients with left hemisphere damage and 30% with right hemisphere damage could be classified as apraxic. Accordingly, it is possible for patients with either left or right hemisphere lesions to exhibit apraxia. In a study with split brain patients who have corpus callosum (connect the two hemispheres of the brain) severed to some degree, Gazzaniga with his colleagues (1998) discovered that the two hemispheres control vastly different aspects of thought and action. Each hemisphere has its own specialization and thus its own limitations and advantages. While the left hemisphere in most individuals plays an important role for semantic and lexicon features of language, the right hemisphere mediates an array of complex functions, including speech prosody, non-verbal communication, and visual-motor tasks. Therefore, both hemispheres make significant contributions to many language functions and control of goal-directed movements.

With the development of new technologies it is now possible to explore hemispheric differences in people with normal brain function in vivo using such as non-invasive brain mapping and cortical stimulation techniques. Kim and colleagues (1993) using functional magnetic resonance imaging (fMRI) measured hemispheric asymmetry in the functional activation of the human motor cortex during contralateral and ipsilateral finger movements. Whereas the right motor cortex was activated mostly during contralateral finger movements in both right-handed and left-handed subjects, the left motor cortex was activated substantially during ipsilateral movements in left-handed subjects and even more so in right-handed subjects (Kim, Ashe, Hendrich, Ellermann, Merkle, Ugurbil, & Georgopoulos, 1993). Besides this fMRI study, a transcranial magnetic stimulation (TMS) study has also reported the similar result. In their study Ghacibeh et al. (2007) observed no ipsilateral motor cortical activation when the contralateral hand was active. In other words, when the motor cortex was already active in controlling movement of a contralateral hand, movement of the hand ipsilateral to that motor cortex did not result in further activation (Ghacibeh, Mirpuri, Drago, Jeong, Hellman, & Triggs, 2007). In another TMS study, Ziemann and Hallett (2001) concluded that the left motor cortex is more active in ipsilateral hand movements in right-handed people, or alternatively, that the left motor cortex exerts more effective inhibitory control over the right motor cortex than vice versa. However, the particular function of left motor cortex activation during left arm movement in right-handed individuals remains uncertain (Goble & Brown, 2008). Additionally, more recent fMRI and TMS studies have shown substantial activation of ipsilateral motor cortex during unilateral hand and arm movements, indicating a role of both hemispheres in controlling each limb (Dassonville, Zhu, Ugurbil, Kim, & Ashe, 1997; Gitelman, Alpert, Kosslyn, Daffner, Scinto, Thompson, & Mesulam, 1996). Dassonville et al. (1997), using a finger tapping task with left- and right-handed subjects, found a clear association between the behavioral lateralization manifested by handedness and functional activation. The volume of activation in the contralateral motor cortex of the right-handed and left-handed subjects was consistently greater during movements of the dominant compared with those of the non-dominant hand. The activation therefore indicated the direction of handedness in these subjects. They also documented a correlation between the degree of handedness and the lateralization of cortical activation during use of the dominant hand. Activation in the motor cortex was more lateralized with increasing degrees of handedness in both right-handed and left-handed subjects. They also discovered a significant ipsilateral activation of the motor cortex during hand movement, which has been a point of controversy in the literature. Although the most significant relation between degree of handedness and functional activation is found for lateralization (which includes both contralateral and ipsilateral activity) in the motor cortex, the essence of this relation is encapsulated in the ipsilateral activation alone. Therefore, it has become clear that during the unilateral arm movements with either left or right arm, there is a substantial activation recorded also in ipsilateral cortex. This suggests the involvement of both hemispheres during unimanual movements.

2.4 Anatomical Correlates for Handedness

More recent researches have shown potential anatomical correlates for handedness. We described the asymmetries in hemispheric function above, and considering those asymmetries, researchers have undertaken potential anatomical substrate for handedness at both macroscopic and microscopic levels.

One study using magnetic resonance morphology showed that the depth of the central sulcus was related to handedness: in right-handers the left central sulcus was deeper than the right, and the opposite pattern was shown for left-handers (Amunts et al., 1996). Furthermore, this macroscopic asymmetry was accompanied by microscopic differences in neutrophil volume, with a greater volume in the hemisphere contralateral to the preferred hand. The authors posit that handedness is associated with more profuse horizontal connections (reflected by the greater neutrophil volume), and the increased intrasulcal surface of the precentral gyrus which may provide a potential substrate for the more complex movements performed by the preferred hand (Amunts et al., 1996). Volkmann et al. (1998) in their study using magnetoencephalography found a significant increase in the volume of the primary motor cortex contralateral side of the preferred hand (Volkmann, Schnitzler, Witte, & Freund, 1998). The results of these studies show asymmetries of neural structures in motor cortex.

Another study looked at the effects of handedness and gender on the depth of the central sulcus in the area of cortical hand presentation (Amunts, Jancke, Mohlberg, Steinmetz, & Zilles, 2000). Strongly male right-handers were found to have a significantly deeper left central sulcus than right central sulcus. Interestingly, the difference in the depth of the central sulcus between the hemispheres was found to decrease significantly from strongly male right-handers, to non-strongly male right-handers, to strongly male left-handers. Even though the same effect was found for the left-handers, 62% of the strongly left-handers had a deeper right central sulcus, this effect was not found significant for the group as a whole. Interestingly, this interhemispheric asymmetry for the central sulcus was not found for the females (Amunts et al., 2000). The results of this study suggest that both the degree of handedness and gender differences may also affect the cortical organization of hand movements.

There are also some TMS studies in the area of motor cortex to find the threshold for eliciting a motor response in different intrinsic and extrinsic muscles of preferred and non-preferred arms. Generally, those works showed that a lower threshold of contralateral brain stimulation is needed to activate preferred arm musculature (Macdonell et al., 1991; Triggs, Calvanio, Macdonell, Cros, & Chiappa, 1994). However, other studies did not show the same asymmetry between preferred and non-preferred arm musculature activation during the brain stimulation (Cicinelli, Traversa, Bassi, Scivoletto, & Rossini, 1997; Civardi, Cavalli, Naldi, Varrasi, & Cantello, 2000). Additionally, TMS has also been used as a means of mapping the extent of various hand and arm representations in the motor cortex. One prominent in this area was conducted by Triggs et al. (1999). They quantified the number of cortical sites eliciting a motor response in two different arm muscles of left and right arms. They found that right-handed subjects had a larger cortical area in the left hemisphere assigned to the targeted muscles than that seen in the right hemisphere which is also consistent with the other studies where used different techniques to map the cortical areas in the brain. In summary, although asymmetries in both brain structures and activations are correlated to handedness, both cerebral hemispheres appear to contribute to unilateral arm and hand movements. The left hemisphere has long been recognized as being dominant for the motor control of skilled voluntary movements in most right-handed individuals; however right hemisphere superiority has also been shown for certain motor functions which is also the main focus of the next topic. Manual asymmetries, as they are observable behaviors, can therefore provide insight into the organization and functioning of the brain.

2.5 The Dynamic Dominance Hypothesis of Motor Lateralization

In the previous topics, we have pointed out the asymmetries between hands and brain structures which may be the evidence for the motor lateralization. Sainburg (2002) first proposed *the dynamic dominance hypothesis* based on evidence suggesting that each hemisphere/limb system is specialized to control of different aspect of movement. This hypothesis is different than other many behavioral approaches to handedness research as they emphasize the performance of non-dominant hand to be inferior for most aspects of movement. This hypothesis was termed as *Dynamic Dominance*, because the dominant arm of right handed people was found to have more efficient and accurate coordination of muscle actions with the complex kinematic and kinetic interactions that occur between the moving segments of the limb (Sainburg, 2002, 2005). The most noticeable biomechanical parameters are *interaction torques*, which are produced when the end of one segment pushes on the end of the other segment through the joint connecting the two segments. Single joint movements can be explained only by the muscle and gravitational torque acting at the joint. However, the multi-joint movements cannot be explained very simply because there are effects of interaction torques due to the rotations of the other joints (Smith & Zernicke, 1987). For example, one can hold the right upper arm with the left hand and move the arm back and forth. If one relaxes the muscles about the right elbow, the forearm will “flop” back and forth. The torque that produces this motion is referred to as an interaction torque. The interaction torque is a load that is self-generated by the movement itself and is absent before the movement begins and can vary with the velocities and accelerations of motion of attached segments which will also vary with the instantaneous configuration of the limb. Therefore to perform the desired multi-joint movement, the CNS should predict the interaction torque and produce the appropriate motor command in advance by taking into account the interaction torque. There is also an essential role of proprioception in coordination of limb segments and cerebral and deafferented patients have shown deficits to deal with interaction torques (Bastian, Martin, Keating, & Thach, 1996; Ghez, Gordon, Ghilardi, Christakos, & Cooper, 1990; Messier, Adamovich, Berkinblit, Tunik, & Poizner, 2003; Sainburg, Ghilardi, Poizner, & Ghez, 1995; Sainburg, Poizner, & Ghez, 1993).

The Dynamic Dominance hypothesis also seems to be more advantageous than other approaches especially when we consider the usage of both arms to accomplish most of daily living activities instead of relying only on dominant arm.

2.5.1 Non-dominant System Specialization for Control of Limb Impedance

The non-dominant system has traditionally been perceived as an inexperienced analog of the dominant hemisphere/limb system because the performance of non-dominant hand is inferior for most aspects of movement (Sainburg, 2010). However, Sainburg (2002) in his study showed better adaptation in terms of final position accuracy to the visuomotor rotation task for the non-dominant arm. In another study, Sainburg and Wang (2002) examined the effects of opposite arm training on visuomotor adaptations. They had two groups of subjects, one that trained using the non-dominant arm first and the other trained using the dominant arm first, and they adapted to a 30° rotation in the visual display during a center-out reaching task. Opposite arm training improved the performance of the initial direction of dominant arm movements, but only the final position accuracy of non-dominant arm movements. These results showed that different aspects of performance transfer in different directions. Thus, this study supports a non-dominant arm advantage in the control of static position. Similar non-dominant arm advantage on final position accuracy has also been found in an assessment of interlimb differences in load compensation (Bagesteiro & Sainburg, 2003). In this study, subjects were asked to make repetitive single joint movements with 20° elbow flexion, while the arm was supported on a horizontal, frictionless air-jet system. On random trials, a 2-kg mass was attached to the subject's forearm prior to the movement initiation and the subject was not informed about the added load nor they could see their arms or the load. Muscle activities were also recorded during execution of the movements. Whereas the dominant arm overcompensated the effects of the load, producing a large and systematic overshoot of final position, the non-dominant arm was able to achieve a level of end point accuracy similar to that found in the un-loaded condition. The electromyographic and kinematic analyses showed that the non-dominant arm compensated for the unknown load through changes in muscle activation occurring post-peak tangential velocity. More efficient load compensation responses for the non-dominant arm supports a specialized role of the non-dominant arm/hemisphere system in sensory feedback mediated error correction mechanism. In another study, Duff and Sainburg (2007) examined adaptation to novel inertial dynamics. In this study, right-handed subjects performed a reaching task toward a single target with either the dominant and non-dominant arm. The first 39 familiarization trials were performed without a load, then a 1.5 kg mass was added to the forearm for the next 180 trials. The aftereffect trials showed lower errors for the non-dominant than the dominant arm. Moreover, as subjects adapted to the inertial load, aftereffect trials displayed progressively larger errors, again only for the dominant arm. These results confirm the idea that the non-dominant system is specialized for control of steady-state limb position at the end of motion. Wang and Sainburg (2007) tested the hypothesis if the non-dominant system specialized for stabilizing limb impedance. They implemented two different tasks: the first one was designed to test reaching movements made from one fixed starting position to three different target positions; other one was designed to test reaching movements made from three different starting positions to one fixed target position. Whereas the dominant arm performance was most accurate when reaching from one fixed starting position to multiple targets as this task condition allows more accurate predictions of task dynamics, the non-dominant arm performance was superior when reaching toward a single target from multiple start locations.

These findings clearly indicate a non-dominant system advantage for achieving and maintaining stable limb position. This advantage is important for mainly two aspects of motor control; firstly stabilizing the limb at the end of a reaching movement and secondly stabilizing an object that is acted on by the dominant arm. Slicing a loaf of bread is a good example to explain this non-dominant arm advantage. During slicing, the dominant arm holds the knife that produces shearing forces on the bread and the non-dominant arm impedes these forces in order to hold the bread still. Maintaining a stable posture in the face of varying forces requires active motor output that is specifically adapted to the imposed loads (Sainburg, 2010).

2.5.2 Dominant System Specialization for Coordination of Limb Dynamics

The initial evidence of dominant system specialization for coordination of limb dynamics was found in a study in which the coordination patterns of left and right arms were examined during targeted reaching movements made by right-handed subjects (Sainburg & Kalakanis, 2000). In this study, movements made by the dominant right arm showed a distinctly different pattern of joint torques than that of produced by the non-dominant left arm. Dominant arm movements were straighter than that of non-dominant arm movements which are reflected by hand path trajectories and were achieved through the more efficient torque strategy on elbow and shoulder joints driven by shoulder muscle actions. In contrast, the more curvature hand paths for the non-dominant arm were associated with increased shoulder excursion because of the effect of elbow muscles through the direct actions on the upper arm and forearm segments.

The study by Sainburg (2002) expanded the findings of Sainburg and Kalakanis (2000) and was the initial formation of *the dynamic dominance hypothesis* of handedness. In this study, Sainburg firstly examined the interlimb differences in adaptation to a novel inertial load by attaching a 1-kg mass eccentric to the forearm axis. He also implemented a visuomotor rotation task to assess visuomotor transformations. In this second task, subjects were required to adapt to a feedback display finger position rotated 30° relative to the start position. The results of these two different tasks indicated clear differences between visuomotor and load adaptation, such that interlimb differences were evident only during adaptation to novel inertial load. Coordination of dominant arm muscle torques was found to be superior across both shoulder and elbow joints, as compared with non-dominant arm muscle torques. This interlimb asymmetry reflects the same result by Sainburg and Kalakanis (2000) in that the dominant arm used significantly less muscle torque than non-dominant arm. Therefore, it was concluded that interlimb asymmetry occur downstream to visuomotor transformations when the trajectory plan is transformed into dynamic properties (Sainburg, 2002).

Subsequent studies by Sainburg and his colleagues extended this hypothesis about right arm dominance for trajectory control. For example, in a task requiring reaching two targets that produces different interaction torques elicited at elbow, Bagesteiro and Sainburg (2002) displayed a more torque-efficient strategy for the dominant arm even though there were small differences with hand-path kinematics between arms. In fact, when movements are matched for speed and displacement for both dominant and non-dominant arm, dominant arm movements consistently use less torque as compared with non-dominant arm movements. Therefore, the coordination differences between the limbs are not simply stem from strength differences. In this study, non-dominant arm movements showed greater torque production, but less efficient movements. These results are also supported with electromyographic (EMG) recordings which implied corresponding differences in EMG profiles between the limbs (Bagesteiro & Sainburg, 2002). The result of the more efficient coordination strategies for the dominant arm movements was also supported in adapting novel dynamic condition (Duff & Sainburg, 2007). In their study, Duff and Sainburg (2007) found that the dominant arm shows progressive improvements in trajectory direction and reductions in curvature which indicates better adaptation for dominant arm to forward dynamic control of movement trajectories during reaching movements. The similar result also found during visuomotor reaching task in coordinating intersegmental dynamics (Shabbott & Sainburg, 2008). In this study, participants were asked to perform targeted reaches in a virtual reality environment in which visuomotor rotations occurred in two directions that elicited corrections with different coordination requirements. The result revealed more curvilinear non-dominant arm movement trajectories than that of dominant arm movement trajectories for corrections with the highest coordination requirement. Moreover, a series of studies have shown interlimb differences on transfer of learning for visuomotor rotations and aimed reaching movements. These studies provide knowledge about what kind of information can transfer from one limb to another. Overall, opposite arm training during visuomotor reaching task or aimed movements from one fixed and different starting positions to one fixed and different target positions resulted in a superior ability of the dominant arm to specify the initial direction of the targeted movement trajectory (Sainburg & Wang, 2002; Wang & Sainburg, 2003, 2004, 2007). In conclusion, these results provide strong evidence for a dominant arm advantage in the coordination of limb dynamics.

This motor lateralization hypothesis has been also supported studies with unilateral stroke and has also implications for understanding the motor deficits resulting from the stroke. In particular, damage to left and right hemisphere has different defections which depend on the side of lesion, and those deficits can be seen in the ipsilateral arm. Each hemisphere has some contributions to control ipsilateral and contralateral arm movements. Therefore, if there is a lesion in sensorimotor cortices and associated areas in one hemisphere, this will produce hemiparesis in the contralesional arm but also should predictable movement deficits in the ipsilesional arm (Sainburg, 2010). In their wide review, Sainburg and Duff (2006) pointed out that whereas stroke patients with right hemisphere damage tend to show deficits in positional accuracy, stroke patients with left hemisphere damage show deficits in trajectory control. Even though patients with severe dominant side hemiplegia must use the non-dominant arm as the main manipulator for daily activities, these deficits have been shown to impede functional performance. However, the non-dominant arm may not spontaneously become efficient as a dominant manipulator, as indicated by the persistence of deficits in chronic stroke patients. Schaefer et al. (2007) recently tested this motor lateralization hypothesis which may predict the nature of ipsilesional motor deficits resulting from unilateral stroke. Right handed healthy control subjects and stroke patients with either left or right hemisphere damage performed aimed single-joint elbow movements of different amplitudes in their ipsilateral hemispace. That is, patients performed the task with their unaffected arm in terms of motor function and were hemiparetic in their contralesional limbs. However, according to the dynamic dominance model of motor lateralization, they hypothesized that left hemisphere damage should produce deficits in initial trajectory features, and right hemisphere damage should produce deficits in final position accuracy. The result for the final position accuracy between the two groups of stroke patients clearly showed that right hemisphere damaged patients displayed substantially more error than their left hemisphere damaged counterparts. It was speculated that the larger errors in final position accuracy for the right hemisphere damaged patients could be related to the restricted ability of these patients to modulate acceleration duration. Some studies showed that variations in the duration of acceleration torque or force are inversely related to the initial magnitude of these variables, and thus appear to compensate for inaccuracies in planning. Therefore, deficit to modulate acceleration duration is associated with larger final position errors. As left hemisphere damaged patients had preserved modulation of acceleration duration, their final position accuracy was much smaller than that of right hemisphere damaged patients. In contrast, left hemisphere damaged patients showed reduced modulation of acceleration amplitude which reflects the ability to modulate torque amplitude to target distance. Therefore, patients with left hemisphere damage suffered from controlling of limb dynamics during reaching that are required for efficient movement coordination. Interestingly, there was not a significant difference between control and both patient groups in terms of movement speed. While neither patient group differed from controls in terms of movement speed, the result indicated that the mechanism, by which speed was specified, through modulation of acceleration amplitude and modulation of acceleration duration, appeared to be differentially affected by left and right hemisphere damage. In summary, these findings support the idea that ipsilesional deficits in stroke patients are differently affected by unilateral stroke in a manner consistent with the idea that each hemisphere is specialized to control of different aspects of movements; left hemisphere for the control of initial trajectory and right hemisphere for the control of final position. Moreover, the contribution of both hemispheres for accurate unilateral arm control is also supported (Schaefer, Haaland, & Sainburg, 2007).

2.6 Reaching Experiments with Hand Preference

When we look at the literature with the topic of hand preference, researchers mainly started to conduct studies in the late 1990s. Even though there were some studies in the late 1980s, those studies focused on handedness and used hand preference to find out the way to assess handedness (Healey, Liederman, & Geschwind, 1986; Steenhuis & Bryden, 1989). In particular, there are two groups of laboratories in Texas A & M University from USA and University of Waterloo from Canada. Researchers from these laboratories conducted very similar studies such that they all investigated the developmental perspective of hand preference and the effect of task difficulty on hand preference.

For the theoretical explanations of hand preference studies, researchers described three possible factors to address this question: *motor dominance*, *object proximity*, and *hemispheric bias*.

Motor dominance was the first explanation that drives people to choose either hand to make a reaching movement. Traditionally, it was assumed that if an individual strongly preferred a particular hand, she or he would probably use that limb to carry out an array of unimanual activities, even in awkward positions (Bryden, Singh, Steenhuis, & Clarkson, 1994). People termed that as *motor* or *limb dominance*. According to this explanation, if someone is right-handed, she or he will use her or his dominant right hand to reach a target or a tool whether or not the target located in the contralateral hemispace. Later on, many studies revealed that motor dominance can only explain the movements made to the ipsilateral hemispace and midline by the dominant hand (Bryden & Roy, 2006; Gabbard & Helbig, 2004; Gabbard, Iteya, & Rabb, 1997; Gabbard, Rabb, & Gentry, 1998). In particular, this explanation seems lacking in regard to identifying the specific attentional mechanisms that influence hand selection programming especially switching to the non-dominant hand after passing the body midline during reaching movements. Therefore, researchers proposed two other explanations that describe this phenomenon.

Initially, it was speculated that programming hand selection involved spatial reasoning based on *proximity* between the closest hand and the object (Gabbard & Helbig, 2004). It is very reasonable to think that the individual consider the biomechanical constraints (e.g., degrees of freedom) involved in accomplishing the task and program the most efficient response, in this case the shortest angular distance based on joint and hand space coordinates (Rosenbaum, 1991; Stins & Michaels, 1997). According to this explanation, using the dominant-right hand to reach contralateral far left hemispace is less biomechanically efficient than reaching ipsilaterally with the closer non-dominant left hand. This idea also parallel with the comfort hypothesis (Mark, Nemeth, Gardner, Dainoff, Paasche, Duffy, & Grandt, 1997) in which it was suggested that an individual's choice of reaching mode in a given situation is driven primarily by postural dynamics. In their study, they treated the arm as a single skeletal degree of freedom (*df*) during reaching and if an additional body part was introduced to the movement, it was considered a multiple-*df* reach. Even though they did not give a choice to the subjects in hand selection, one might use this idea to explain why individuals may prefer to use non-dominant hand on its own hemispace. It seems very possible that reaching to left hemispace with the dominant-right hand would require a multiple-*df* reach, which is relatively less efficient. Therefore, according to object proximity idea, people consider the proximity between the reaching hand and the object when they program the reaching movements.

Another theoretical perspective suggests an explanation considering *hemispheric bias* which is in favor of the hand on the same side as the stimulus. Harris and Carlson (1993) observed this pattern of behavior in their hand preference study for visually-guided reaching movements in children and adults. They found out that when objects were placed off the midline, both groups reached more often with the same-side hand, regardless of whether it was the dominant or non-dominant hand. They concluded that the object locations strongly affect the hand preference and explained this behavior by the principle of “minimal effort”. The further supports in favor of the hemispheric bias came from movement and reaction time studies (Carnahan, 1998; Mieschke, Elliott, Helsen, Carson, & Coull, 2001). In these studies, researchers discovered that each hand display superior performance in its own hemispace except for the body midline. For the body midline, right hand displayed better performance than left hand of right-handers in terms of movement time because right hand was faster than left hand. Biomechanical factors can also play some roles to make efficient movements with the limb on the same side of working space (Gabbard & Rabb, 2000). Thus, this explanation is also very close to object proximity idea such that both of them consider the biomechanical constraints to make efficient reaching movements.

In general, these three explanations for the question “what drives people to select a hand to reach a target or toll” are not strong enough to find out this problem. They have some theoretical explanations to describe this phenomenon but none could give any quantitative data for better explanation. Therefore, this phenomenon needs to be solved. There are many studies attempted to discover this problem and we will discuss these studies with the context of these three explanations.

One of the first attempts to examine the factors affecting hand preference was conducted by Gabbard, Iteya, and Rabb (1997). In their study, they examined hypothesized differences between right- and left-handers on a unimanual task involving object proximity. Strongly right- and left-handed subjects were tested in task which required them to pick up a foam cube located 10° to 70° from midline in left and right hemispace. There was a more mark for the cube position and it was located at the midline of the each subject (90° represented the traditional midline). The subject was instructed to pick up the cube using either hand and put it in a box at the midline in front of them; this was repeated for the nine positions (one trial per position). They found that the distribution of dominant hand usage among left- and right-handed subjects was different across work space. Whereas right-handed subjects used their dominant hand on its own hemispace, midline, and left hemispace, left-handed subjects tended to use their dominant hand on the left hemispace and midline. The usage of dominant hand in left-handers dramatically decreased on the contralateral hemispace. However, right-handed subjects used their dominant hand to pick up the cube still on the position located next to the body midline in the contralateral hemispace. The authors concluded that right-handers are more lateralized than left-handers as left-handers are more adaptable to “right-handers world”. Moreover, they speculated that attentional information derived from object location affected programming by “overriding” the motor dominance factor in decision making for actions in what would be contralateral space. Decision making and programming involved some type of spatial reasoning based on proximity between closest hand and the object. Individuals make their decisions considering biomechanical constrains of the movement and in most cases, the most efficient and comfortable response; perhaps the shortest angular distance based on joint and hand space coordinates (Scott & Kalaska, 1997; Stins & Michaels, 1997). In this study, the reason why right-handed participants switched to use their non-dominant hands in contralateral hemispace may be related to less biomechanically efficient movements than to reach with the closer left hand (Gabbard, Iteya, & Rabb, 1997).

In the subsequent study, Gabbard, Rabb, and Gentry (1998) looked the developmental characteristic associated with this phenomenon. That is, they asked if the children use attentional information as effectively as adults during programming hand selection. Using the same experimental paradigm that described above, they had two groups of subject. One group was consisted 75 right-handed subjects with the mean age being 21 years. The other group was consisted 66 right-handed children with the mean age being 6 years. The result for the adult group revealed the parallel finding with the previous study. That is, the participants preferred to use the hand that is ipsilateral to the target location. Although the children also applied the same pattern, they tended to be more consistent the use of their dominant limb across hemispace positions in the context of this study. They even used their dominant hand to pick up the foam in the furthest left position. Considering left hemispace positions, children again used their dominant hand across left hemispace as twice as adults (52% versus 26.5%). They concluded that adults use attentional information more efficiently to program movements for contralateral space and maturation to use attentional information together with habitual use of dominant hand may explain this result (Gabbard, Rabb, & Gentry, 1998).

Some other attempts were made to find out the developmental effect of hand preference (Bryden & Roy, 2006; Carlier, Doyen, & Lamard, 2006; Gabbard & Helbig, 2004; Leconte & Fagard, 2006). Gabbard and Helbig extended their previous study with including arm-crossed condition. In their previous study, subjects had their arms uncrossed and the authors implemented this arm-crossed condition to differentiate hemispheric bias and object proximity explanations. Strongly right-handed children were asked to reach and pick up a small object across the working space beginning with the arms uncrossed and arms-crossed. They administered an imagined and actual movement execution with the arms-crossed condition. The uncrossed condition showed the same result with the previous study. That is, participants reached ipsilaterally using the hand on the same side as the stimulus, thus supporting the explanations of both object proximity and hemispheric bias. However, the arms-crossed condition showed that vast majority of participants preferred keeping their arms crossed in response to right and left hemispace stimuli. This leads to suggestion that object proximity rather than hemispheric bias was the driving factor in this context and this was the same for the previous studies conducted with the adults (Gabbard & Rabb, 2001; Helbig & Gabbard, 2004). Participant showed the same pattern for imagined and actual movements. Overall, authors concluded that hand selection is task and context dependent (Gabbard & Helbig, 2004). Somewhat similar results were also found in other studies stating that adults can make more efficient use of spatial information to program their reaching movements, object proximity together with hemispheric bias explain for understanding hand preference, and hand preference depends on task demands and environmental context (Bryden & Roy, 2006; Carlier, Doyen, & Lamard, 2006; Leconte & Fagard, 2006).

Task or skill demands were also found a factor that may affect hand preference in some studies (Mamolo, Roy, Bryden, & Rohr, 2004; Mamolo, Roy, Rohr, & Bryden, 2006). In both studies they used a design in which strongly right-handed adults were asked to make reaching movements to one of five tools located in an array. Participants were required to pick up the tool, pick up and demonstrate how to use it, or pick up and actually use the tool on the materials provided. The results showed that with increasing task difficulty, i.e. pick up the tool and use it, the frequency of dominant right-hand usage also increased. This is in spite of the biomechanical inefficiency associated with this strategy, since the participant must reach across their body to perform the task. Although right-handers use their dominant hand more across working space with the increased task demands, left-handers do not show the same pattern. That is, left-handers switch to their non-dominant hand on the contralateral space. The possible explanation may be that left-handers have adapted to an environment designed for right-handers (Mamolo, Roy, Bryden, & Rohr, 2004).

Helbig and Gabbard (2004) further researched the idea if 1- and multiple-*df* reaching movements can play a role for hand selection. They videotaped right-handed participants' movements during reaching to grasp a cube and categorized the movements as 1- and multiple-*df* with considering if they rotated their torsos or leaned forward. They found out that during 1-df reaches, even though participants could reach the stimulus with their dominant hand using only a 1-df movement in the left hemispace, they continued to prefer the non-dominant hand for that location. Whereas motor dominance may be the primary driving factor in programming and executing reaching movements at the midline and dominant side of hemispace, attentional information appears to override this factor to influence the programming of movements in response to stimuli present in contralateral space (Helbig & Gabbard, 2004).

The first attempt for kinematic analysis to discover the pattern of hand selection during reaching was made by Stins, Kadar, and Costall (2001). They had both left- and right-handers groups in their study and asked subjects to reach out and pick up an object with either the left or right hand. There were 7 glasses located horizontally to the subject position and were placed so that subjects could reach them with either hand. Subjects' movements were recorded by two infrared cameras during the reaching. They calculated movement time (MT), acceleration time (AT), and deceleration time (DT). They also looked the accuracy demand with having the glasses filled and empty. It was found that the further away from the body midline a target object was located, the greater the probability that ipsilateral hand was selected to pick up the glass which is consistent with previous studies. However, the tendency to continue using a hand in the contralateral space was greater for the preferred hand than the non-preferred hand. In addition, there was a marginally increase in the use of the preferred hand when the accuracy demands were high (filled glass) as opposed to low (empty glass). In terms of kinematics, they found that the transition point (near to the midline) corresponding to the shift between the two hands correlated with the point where their deceleration times were equal, but these locations closely coincided. These findings suggest that people are highly skill perceivers of their own action capabilities, and that they are able to select the action mode that is most suited to perform a given task (Stins, Kadar, & Costall, 2001). Even though the authors found that DT might be a factor affecting people choice of hand, they commented that this needs to be sought at a deeper level and should include other kinematic and kinetic variables.

The other attempt to find out a kinematic explanation for hand selection phenomenon was made by Kim et al. (2007). In previous studies, it was found that the switch from dominant hand to non-dominant hand occur the position located near left to the body midline approximately 20° horizontally from sagital plane (Gabbard & Helbig, 2004; Gabbard & Rabb, 2001; Helbig & Gabbard, 2004). Following these consistent results, Kim et al. asked to 13 strongly right-handed people to reach one of five objects located only on the left hemispace (50°, 60°, 70°, 80°, and 90°) with the left and right hand which was assigned before movement rather than free selection. During reaching to these objects, their movements were recorded with an OPTOTRAK 3020 camera system. They calculated MT, AT, DT, and hand path linearity (PL) and compared right and left hand reaches with considering these variables. The results revealed a significant left hand advantage in terms of MT, AT, DT for the object positions in 50°, 60°, and 70°. That is, there was no advantage of right hand in terms of planning and feedback processing to these locations which suggests that open- and closed-loop processes could not explain the limb selection behavior. Consistent with previous results (Bagesteiro & Sainburg, 2002; Sainburg, 2002; Sainburg & Kalakanis, 2000), right hand's PL did not change across the five object locations, whereas left hand's PL changed significantly across the same hemispace. PL for left hand on 50° position was more curved than the other positions and less curved on 80° and 90° positions. Moreover, there was no clear advantage of left-hand and right-hand reaches for the 80° and 90° positions. Their explanation was that when the reaching movement requires more degrees of freedom with both hands, then the probability to use either hand may increase. Therefore, this may be an explanation why people reach with their dominant right hand to the near left location from the body midline. Finally, they concluded that right hand reaches to the 80° and 90° positions among strongly right-handers may stem from more efficient use of shoulder interactive torque in both left and right hemispaces which was found in earlier works of Sainburg and his colleagues (Bagesteiro & Sainburg, 2002; Kim, Gabbard, Buchanan, & Ryu, 2007; Sainburg, 2002; Sainburg & Kalakanis, 2000).

Taken together all the studies on the topic of hand selection, researchers have first focused on the general distribution of left and right hand usage in the working space; however, they have hardly addressed the question as to why people choose one hand over the other in the first place. They tried to find possible explanations to address the question what drives people to select a hand as opposed to another during the reaching movements. At the beginning, they enlightened this hand selection behavior with three theoretical explanations; *motor dominance*, *object proximity*, and *hemispheric bias*. These explanations only theoretically clarified the hand selection behavior and could not have a quantitative support. Recently, there were two attempts (Kim et al., 2007; Stins, Kadar, & Costall, 2001) to explain this phenomenon with kinematic variables but none of them found an actual answer to this phenomenon and Kim et al. (2007) referred to the earlier works of Sainburg and his colleagues (Bagesteiro & Sainburg, 2002; Sainburg, 2002; Sainburg & Kalakanis, 2000).

In this dissertation; therefore, three experiments were conducted based on the idea if motor asymmetries between hands can affect the hand preference during reaching movements.

CHAPTER 3

EXPERIMENT 1

3.1 Introduction

Reaching for and grasping objects in the workspace is an activity we perform many times every day, for instance when pushing a button on a keyboard or grasping a pen from the table. If the activities do not require additional task, people can use either hand to perform these activities. Researchers found that right-handed people tend to use their dominant hand approximately 60% of the workspace to reach and pick up an object (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003). This means that right handed people use their dominant hand on the right hemispace, on the middle point of the body, and on the left hemispace close to the midline of the body. Therefore, right handed people prefer to reach even to the contralateral hemispace closer to the midline with their dominant hand. Researchers explained this hand preference phenomenon considering the proximity and hemispheric bias (Gabbard & Rabb, 2001; Mamolo et. al., 2004; Stins, Kadar, & Costall, 2001). As we mentioned earlier, these explanations are based on theoretical clarifications and are not supported with the quantitative data. Moreover, studies related to hand preference were limited to have only 7 or 9 targets positioned in the arc design distanced at approximately 70% of arm length thus the space closer to the body was not explored.

Recently, Kim et al. (2007) has examined the underlying mechanisms of hand preference with the kinematic data. They showed that the reason why strongly lateralized right-handers choose right hand to reach towards contralateral hemispace next to the midline might stem from more efficient use of shoulder interactive torque (the rotational effect of the forces on elbow resulting from motion of the shoulder) in both left and right hemispace which was found in the earlier Sainburg (2002) and Sainburg and Kalakanis studies (2000). Sainburg (2002) termed this lateralization of movement control strategies as "*Dynamic Dominance Hypothesis*" on the basis of multiple studies examining targeted reaching in both healthy and stroke patients. According to this hypothesis, non-dominant hemisphere is specialized for control of steady state limb position, and dominant hemisphere is specialized for control of movement trajectory during reaching. These asymmetries in sensorimotor performance likely give rise to handedness which is commonly assessed by questionnaires. Therefore, there is a need to test if sensorimotor performance differences may affect choice of hand during reaching movements.

3.2 The Purpose of the Study

In the literature, it has been stated that there is an asymmetry between hands on sensorimotor performance and this asymmetry may lead to handedness. Therefore, the aim of the experiment 1 is to find whether limb selection is, in fact, based on sensorimotor performance asymmetries. Moreover, we also aim to find the effect of distance amplitude on hand preference which is not stated in previous studies.

3.3 *The Hypotheses*

1. Based on previous findings, right hand reaching frequency will be more than that of left hand.
2. There will be an effect of distance amplitude on hand preference.
3. Because it has been previously shown that dominant and non-dominant arms are specialized for different aspects of movement during reaching, we hypothesize that the dynamic requirements of the task will influence hand selection for reaching tasks.
4. Left and right hands' performances will be significantly different in terms of final position error, hand path linearity, and combined joint work during the reaching movements.

3.4 *Materials and Methods*

3.4.1 *Participants*

Twenty-four participants (12 females & 12 males) aged between 18-34 years old (M_{age}= 24.8, SD=3.9) signed the consent form approved by the Institutional Review Board of the Pennsylvania State University. Participants were voluntarily enrolled in this study. To meet the requirements of the study, participants had to be healthy with a sedentary life style that had no regular sports backgrounds. All participants were strongly right-handed. We used the 12 item Edinburgh Inventory (Oldfield, 1971) to assess the handedness. According to this inventory, scores > 95% are qualified as strong handedness. Thus, we used this criterion to include participants into the study. They were grouped with respect to experimental design in a pseudo-randomized manner to make sure that the gender was equally represented in each testing condition.

The exact nature of the experiment aim was explained to each voluntary participant. Everybody was paid minimum wage for his or her participation.

3.4.2 Experimental Setup

Experimental setup is shown in Figure 1. Participants were strapped to the chair with arms supported on the air sleds to minimize the effects of gravitational and frictional forces as well as to avoid fatigue during the experiment. The custom made application programmed in REAL BASIC (REAL Software, USA) on a Macintosh computer was used to provide an interactive game of reaching to targets in the frontal space. Participants were shown a veridical display of cursors representing index finger of each hand, the start and target positions, and the feedback in the form of the cursor displacement path and scoring. This video was projected from the 52” HDTV (Sony Electronic Inc.) onto the mirror that covered subjects’ arms. An electromagnetic tracking system Flock of Birds (Ascension Technology, USA) with four 6 degrees of freedom sensors was used to measure elbow and shoulder joint displacement including distal and proximal anatomical landmarks of the forearm and upper arm. Sensors were firmly attached to both upper arm and forearm segments approximately in their centers. Note that all joints distal from elbow were immobilized with the splint to create two-segment arm system. Displacements of joints and anatomical landmarks were measured with approximate accuracy of 2 mm^3 at the 103Hz frequency and later subjected to processing and analysis using IgorPro (Wavemetric, Inc., USA). Joint displacements data were filtered using 8Hz dual-pass digital filter and velocities and accelerations were computed using numerical derivations. The dimension of table top is 2 m in horizontal and 1.5 m in vertical plane.

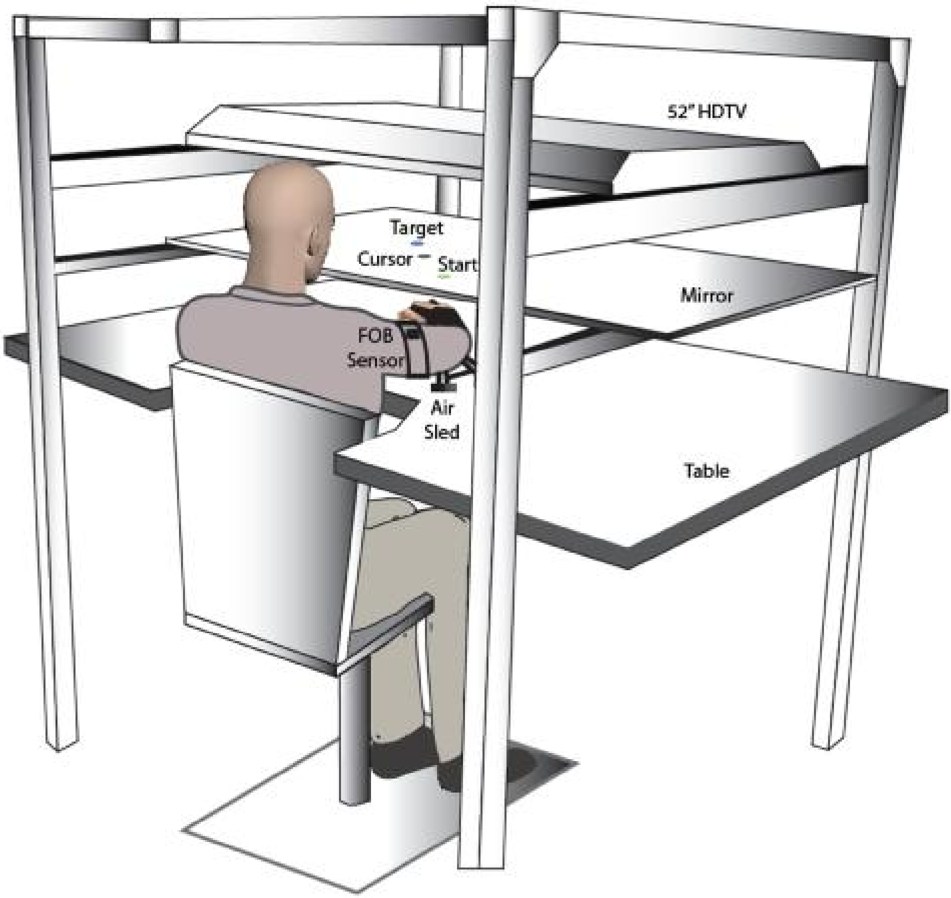

Figure 1. The Experimental Setup

3.4.3 *Experimental Design*

In the experiment 1, the visual feedback (FB) of the cursor representing the tip of the index finger was provided. Thus, in the FB condition participant saw the cursor during the movement and between the trails. This experiment consisted of three conditions: choice of hand, forced right- and forced left-hand reaching movements to targets positioned across the frontal workspace. Whereas the choice of hand condition tested frequency of selected hand, the forced hand conditions provided equal data sample for both hands to examine movement accuracy, quality and efficiency.

The matrix of 32 targets located in the frontal space is shown in Figure 2 These targets were arranged for each individual with respect to subject's arms size and initial joint angles. Firstly, the locations of starting positions were identified for each subject based on these initial joint angles with shoulder external and elbow internal angles being 25 and 75 deg respectively. In order to avoid any visual and spatial asymmetry between targets, the location of starting positions in parasagittal planes were averaged across left and right hand. Note that maximum effort was made to setup each subject as symmetrical as possible so these differences were very small thus irrelevant. The lines of targets in transverse plane (horizontal in Figure 2) were set up at 25, 40, 55 and 70% of the distance averaged across hands between the starting positions and the tip of the index finger for fully extended arms. The lines of targets in parasagittal planes (vertical in Fig 2) were spaced symmetrically from the midsagittal plane into the left and the right hemispace by a quarter of the distance between the start positions. This design aimed to achieve dense sampling of frontal space.

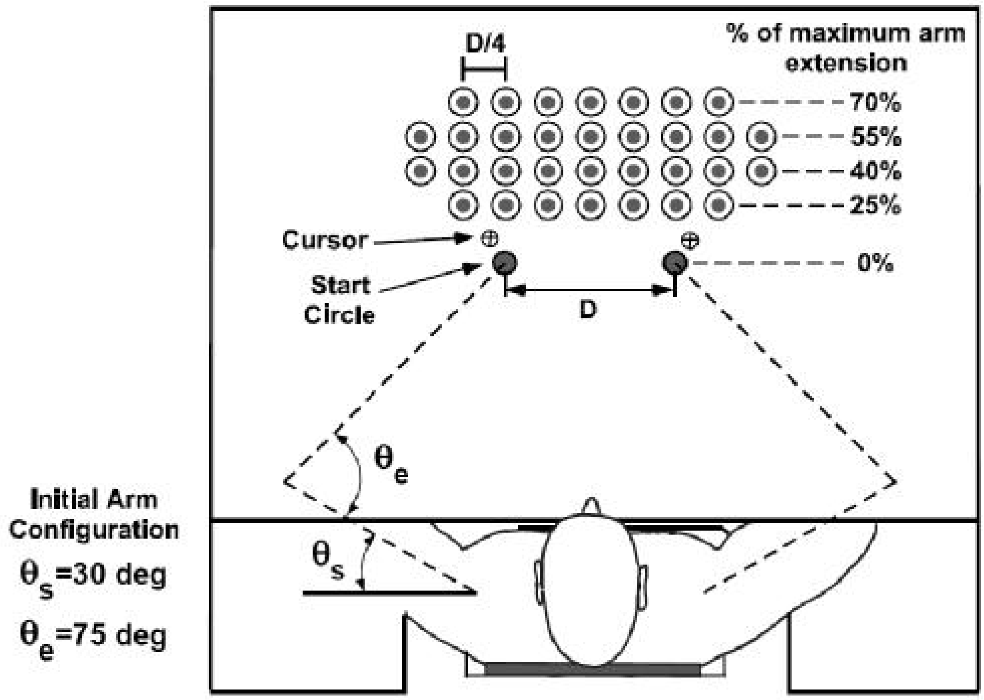

Figure 2. The distribution of the matrix of 32 targets in the working space

3.4.4 Experimental Task

Participants were asked to perform 320 reaching movements (10 per target) from the start circles (2 cm in diameter) that represented starting positions to targets (3.5 cm in diameter), which were presented in pseudo-randomized order. In order to minimize a plausible effect of previous trial on the choice of the hand, the reaches to targets in the middle region of the frontal space preceded reaches to either left or right targets in the equally balanced manner. Participants were instructed to reach to the target rapidly while maintaining accuracy and stop on the target with no additional corrections. Trials were 1 sec in duration and were initiated with the beep signal after both cursors (1.25 cm in diameter cross hair) were hold in the start circles for the duration of 0.3 sec.

The targets were displayed prior to the trial initiation giving a subject as much time as required for deciding on which hand will be used. Accuracy was rewarded with 10, 3 and 1 point for landing within 3.5, 4.5 and 5.5 cm diameter from the center of the target respectively. These points were provided to motivate the participants during the experiment. After each trial, feedback about the score and performed cursor path were displayed for 1 sec. This cursor path was shown in the form of small circles (1 cm in diameter) that represented data of cursor locations during the trial.

3.4.5 Data Analysis

Initially, three regions of interest were identified in the frontal workspace in the FB experiment. The criteria of qualifying targets to these regions were based on the mean frequency of reaching across subjects in the choice of hand condition. This approach can be justified by our interest in examining the space where subjects transitioned from using predominantly their dominant right to use the non-dominant left hand. Therefore, we initially defined the midline of reaching frequency (MF) using targets to which the distribution of reaches between hands was similar. The remaining targets located to the left from the MF and symmetrical targets located to the right from the MF were grouped to represent the left (LF) and the right (RF) hand usage areas (see Figures 3). In these areas of interest but in the forced hand conditions, six dependent variables that depict sensorimotor performance were quantified across subjects. Three dependent variables were tangential velocity, acceleration, and deceleration. These dependent variables give us information about speed of the movements with the directions and increase and decrease in the magnitude of velocity. The other three dependent variables included: accuracy characterized by the final position error (FPE), movement quality characterized by the hand path linearity (HPL) and energetic efficiency characterized by combined joint work (CJW) performed by muscles to accelerate/decelerate arm segments. Please note that FPE, HPL, and CJW were used to explain hand choice behavior. The FPE was defined as the shortest distance between the final position of the cursor (index finger) and the center of the target:

$FPE = \sqrt{(x_e - x_t)^2 + (y_e - y_t)^2}$, where (x_e, y_e) and (x_t, y_t) are coordinates of the final position of the cursor (index finger) and the center of the target respectively. The HPL was defined as the ratio between minor and major axis with the major axis being the furthest distance between any two points given on the hand path and the minor axis being the furthest distance perpendicular to the major axis from any given point on the hand path. The CJW was defined as the sum of shoulder and elbow joint work, which were computed using trapezoidal integration of the product of absolute muscle torque derived from inverse dynamics analysis and angular joint velocity:

$$CJW = \sum_{i=1}^{n} \left(\frac{(\left|t_{S_{i-1}}\right| \times w_{S_{i-1}} + \left|t_{S_i}\right| \times w_{S_i})}{2} \right) \times \Delta t + \sum_{i=1}^{n} \left(\frac{(\left|t_{E_{i-1}}\right| \times w_{E_{i-1}} + \left|t_{E_i}\right| \times w_{E_i})}{2} \right) \times \Delta t$$

where τ_S and τ_E are muscle torques and ω_S and ω_E are angular velocities of shoulder and elbow joints respectively; indexes ***i-1*** and ***n*** are points of movement initiation and completion respectively; and $\Delta t \cong 0.01$ sec is the interval between two measurement points that were recorded at the frequency of 103Hz over duration of 1 second as explained earlier.

The statistical analysis was performed using two-way repeated measures ANOVA with subject being a random factor. This analysis was based on hand (2) by target (32) interaction for the reaching frequency and on hand (2) by regions of targets (3) interaction for other three dependent variables. Post-hoc analysis was performed using Tukey HSD (Honestly Significant Difference) test. The level of significance was set to $p<0.05$ and was computed using JMP 8.0 statistical package (SAS Institute, USA).

3.5 Results

In the FB choice of hand condition across all targets, participants reached using the right hand more frequently than using the left (68% vs. 32%) as shown in Figure 4. The repeated measures ANOVA showed a significant 2-way interaction (2x32) between hand (L & R) and target (1-32) ($F_{(31,441)}=135.03$, $p=.0001$). Since one of the main interests of this study was to compare reaching frequency between hands; thus, analysis across targets within hand was omitted. In Figure 3, we show the distribution of reaching frequency for all targets averaged across subjects. Note that three regions (LF, MF and RF) of targets were outlined to emphasize spatial division with respect to reaching frequency. As described earlier (see Methods), we initially identified the MF region that included targets, where the differences between hands in reaching frequency were found to be not significant ($p=.57$, Tukey HSD). In the FB condition, this MF group consisted of four targets with the mean differences across subjects ranging between 2.5%-20%. The LF group included all targets (n=9) to the left side of the MF and these were reached using mostly the left hand with frequency above 75% ($p=.001$, Tukey HSD). The RF group consisted of analogues targets to the right side, which were symmetrical to the LF group with respect to the MF region. These RF targets were reached using mostly the right hand also with the frequency above 75% ($p=.001$, Tukey HSD). The main finding here is that the MF group of targets is shifted into the left space and this shift increases with larger distance amplitude. This effect of target distance amplitude was found to be significant ($p=.001$, Tukey HSD) when comparing the shortest with the longest targets in the first two parasagittal planes to the left side from the midline of the body. Although not significant (p=.57, Tukey HSD), similar trends were observed in the parasagittal plane further to the left side with the right hand usage increasing from the bottom (7.5±3.1%) to the top target (27.5±4.9%) as well as on the other side in the midline of the body, where the right hand usage increased from 80.0±6.3 to 96.2±2.6% respectively. In Figure 3, we can see that there are very few left hand reaches to the furthest right hemisphere on the second line and on the line furthest from the body. When we looked to the individual data, we realized that one subject made only one reach to those targets. The previous trials of those left hand reaches to the furthest right hemisphere targets were made by either left or right hands; thus, there is no systematic reason to explain this behavior.

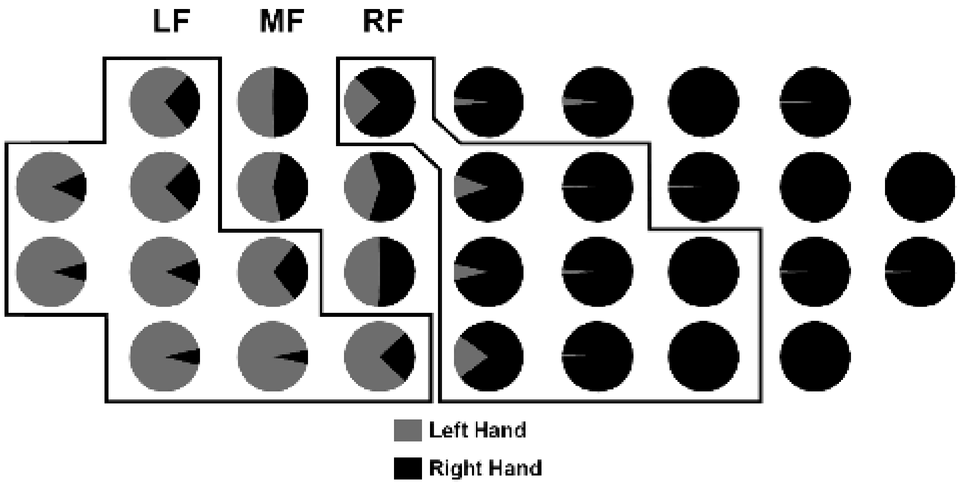

Figure 3. Pie chart of reaching frequency between hands with the distribution of all targets averaged across subjects in FB condition.

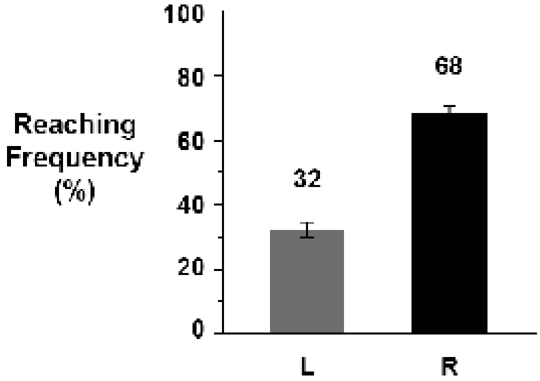

Figure 4. Mean of reaching frequency between hands across all targets and subjects in FB condition.

As described previously (see Methods), six dependent variables that were determined as accuracy (FPE), quality (HPL), velocity, acceleration, deceleration, and efficiency (CJW) of the movement were subjected to repeated measures ANOVA. These dependent measures were collapsed across targets grouped in LF, MF and RF in the forced right- or left-hand conditions to make interlimb comparisons in reaching movement performance.

Firstly, the movement accuracy defined by the FPE ranged between .010-.019 m across hands and targets being on average 0.013±0.0002 and 0.015±0.0004 m for the right and left hand respectively as shown in Figure 5. In general, the right hand was found to have a slight advantage across most of the targets in the workspace. This was also the case for the average values across target regions as shown in Figure 6. However, there was no significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F_{(2,332)}=2.68$, $p=.07$). Moreover, there was no significant effect of neither hand ($F_{(1,14)}=0.45$, $p=.51$) nor target regions ($F_{(2,332)}=1.06$, $p=.35$) on the FPE. Overall, there is no advantage in movement accuracy across both hands and target regions.

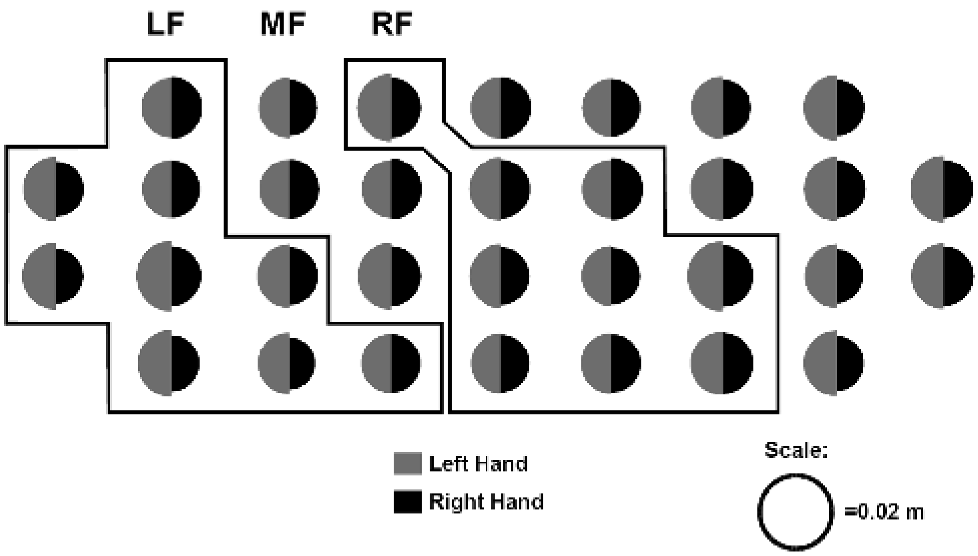

Figure 5. Mushroom plot of FPE between hands with the distribution of all targets averaged across subjects in FB condition.

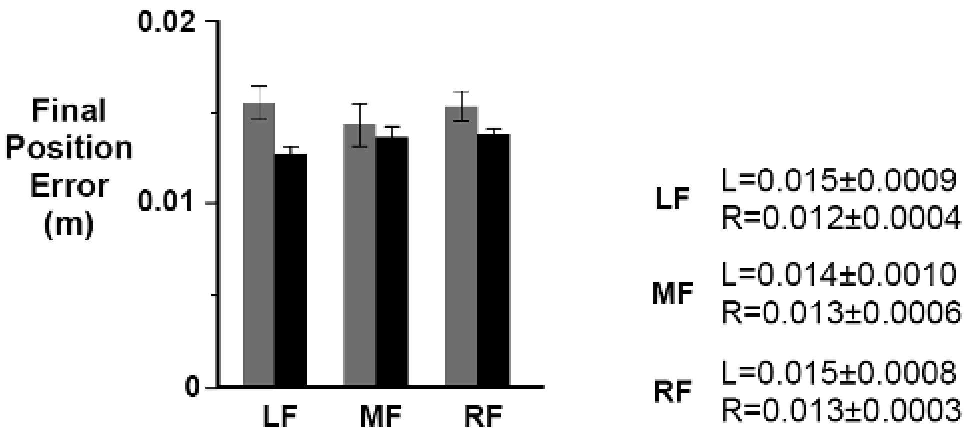

Figure 6. The mean of FPE values across targets regions in FB condition.

The second dependent measure of the sensorimotor performance is the HPL that was used as the estimate of the movement quality. This HPL varied across the workspace with the most curved movements to the shortest targets in the central region for both hands and the least curved movements to the shortest targets in the ipsilateral side for the right hand as shown in Figure 7. Three exemplar trials from three regions display hand path linearity and velocity profiles of three targets located furthest distance to the body (Figure 9A and 9B). The hand path for right hand in the RF region is more linear than that for left hand. However, both hands' movements are very similar in terms of linearity in the MF and LF regions. Overall, the HPL ranged on average between 0.03 and 0.08 across the whole workspace. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L and R) and target regions (LF, MF and RF) ($F_{(2,332)}$=12.03, p=.001). As shown in Figure 8, the HPL measures in the MF region were 0.063±0.002 and 0.064±0.002 for the right and left hand respectively, which was found to be not significant (p=.99, Tukey HSD). Although on average the left hand showed a slight advantage in the LF region, the post hoc analysis revealed no significant effect of hand (p=.93, Tukey HSD). Similar to the previous finding (Bagesterio & Sainburg, 2002), the measures of the HPL in the RF region showed a significant disadvantage of the left hand (0.076±0.002 vs. 0.060±0.003, p=.0001, Tukey HSD). It should be realized that the HPL in the MF and RF regions reflect the hand selection behavior.

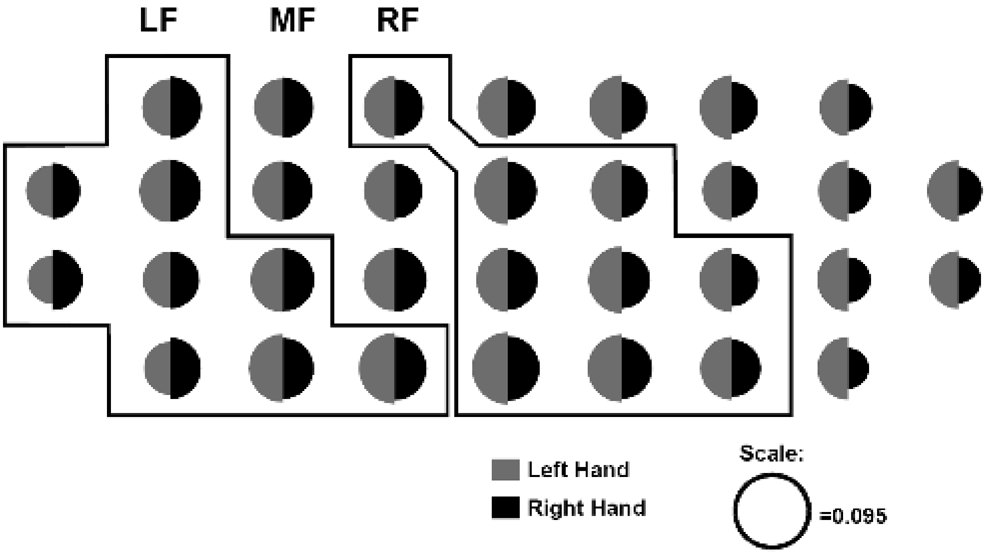

Figure 7. Mushroom plot of HPL between hands with the distribution of all targets averaged across subjects in FB condition.

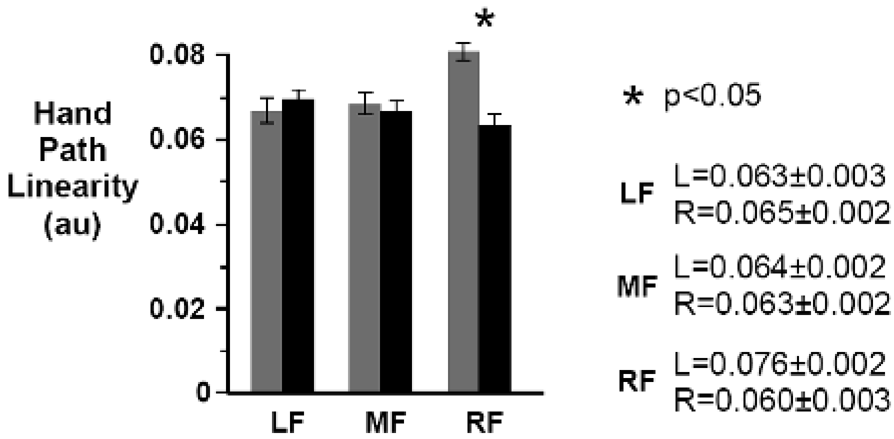

Figure 8. The mean of HPL values across targets regions in FB condition, $p<0.05$.

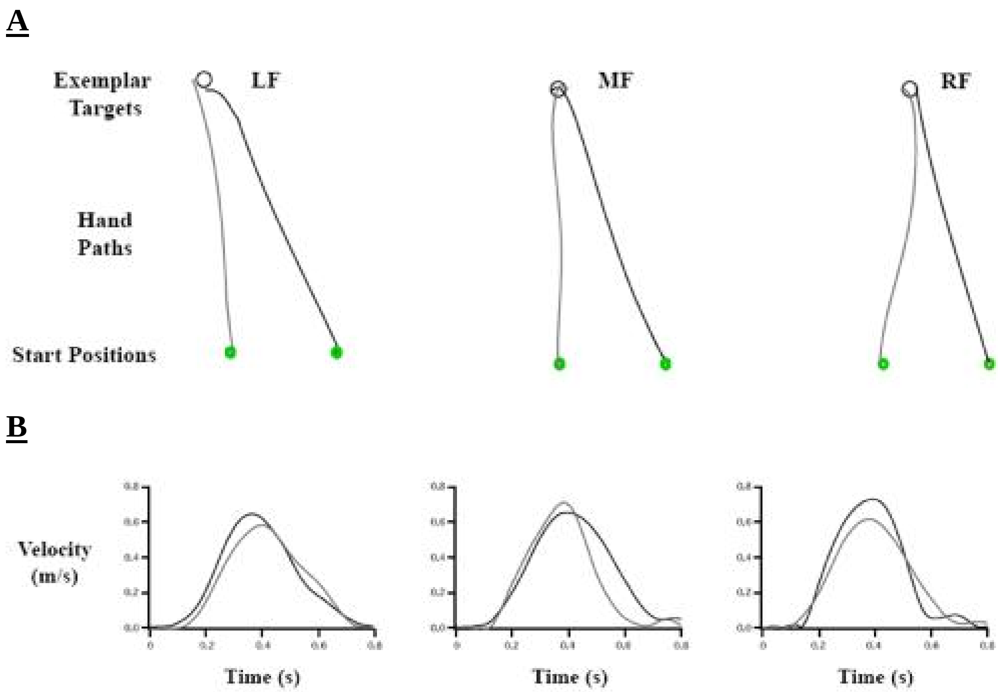

Figure 9 (A-B). HPL (A) and velocity profiles (B) of three exemplar trials from three regions of three targets located furthest distance to the body.

We also compared velocity profiles of left and right hand reaches in those three target regions. Please note that we had a requirement for the completion of trials. Trials were 1 sec in duration; therefore, each trial had to be performed within this time duration. In figure 10, we see that left hand reaches are faster in the RF region but slower in the MF and LF regions. However, right hand reaches are substantially faster in the MF and LF regions. The repeated measures ANOVA displayed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F_{(2,332)}$=22.82, p=.0001) for the velocity. Left hand reaches were significantly faster than right hand reaches in the RF region (0.55 m/s vs. 0.49 m/s, p=.007, Tukey HSD). In the MF region, even though right hand reaches were faster than left hand reaches, that was not found to be significantly different (0.63 m/s vs. 0.57 m/s, p=.24, Tukey HSD). Opposite to the RF region, right hand showed significantly faster reaches than left hand reaches in the LF region (0.61 m/s vs. 0.50 m/s, p=.0001, Tukey HSD). Each hand should move faster to the contralateral hemispace than to the ipsilateral hemispace as there was a time limitation to complete the trials. Reaching to the contralateral hemispace requires moving further distance than reaching to the ipsilateral hemispace. Considering the time limitation and distance to move, these obtained findings in velocity were expected.

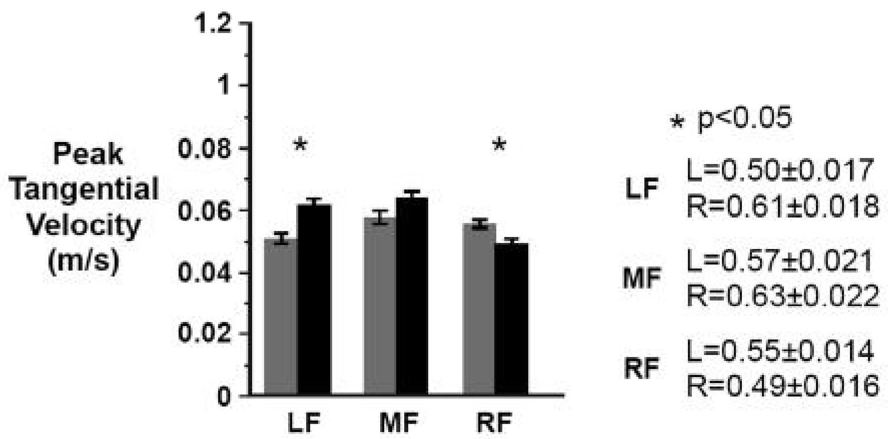

Figure 10. The mean of peak tangential velocity across target regions in FB condition, $p<0.05$.

The peak tangential acceleration profiles of left and right hand reaches in three regions which represent an increase in the magnitude of velocity were displayed in Figure 11. Tangential acceleration profiles show very similar pattern like velocity profiles except for RF region. As one may expect, acceleration is higher in MF and LF regions for right hand than left hand. On the other hand, acceleration is very similar for both hands in RF region. Statistical analysis of repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F_{(2,332)}$=6.83, p=.001) for acceleration. Post-hoc analysis revealed that acceleration is significantly higher for right hand than for left hand both in MF (3.91 m/s^2 vs. 3.47 m/s^2, p=.04, Tukey HSD) and in LF (3.90 m/s^2 vs. 3.55 m/s^2, p=.006, Tukey HSD) regions. However, there was no significant difference in RF region between hands (left hand: 3.31 m/s^2 & right hand: 3.21 m/s^2, p=.92). Even though left hand reaches showed faster movements than right hand reaches in the RF region, acceleration profiles did not change in that region for both hands.

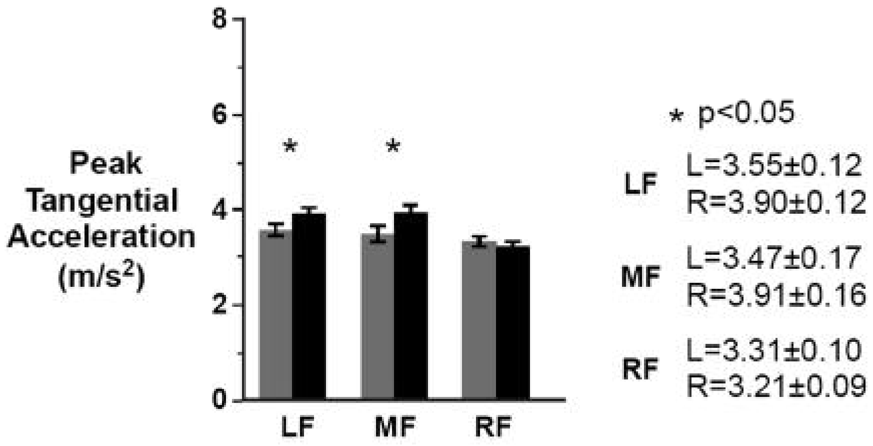

Figure 11. The mean of peak tangential acceleration across target regions in FB condition, p<0.05.

The other variable which represents a decrease in the magnitude of velocity is deceleration and was shown in Figure 12. The max tangential deceleration looks very similar for both hands in all regions. The repeated measures ANOVA showed no main effect of hand ($F_{(1,14)}$=0.05, p=.99) and no interaction between hands and three regions ($F_{(2,332)}$=0.97, p=.37). There was a main effect of target regions ($F_{(2,332)}$=10.25, p=.001). Post-hoc analysis revealed that mean deceleration was slower in the RF region (2.52 m/s^2) than in the MF (2.85 m/s^2)

and in the LF (2.70 m/s^2) regions. These results indicate that both hands achieve the same deceleration regardless of target regions. Therefore, the distance of targets does not have an effect of peak deceleration during reaching. For instance, when right hand reaches to the contralateral hemispace, it can produce max deceleration as the same when left hand reaches to the ipsilateral hemispace or vice versa.

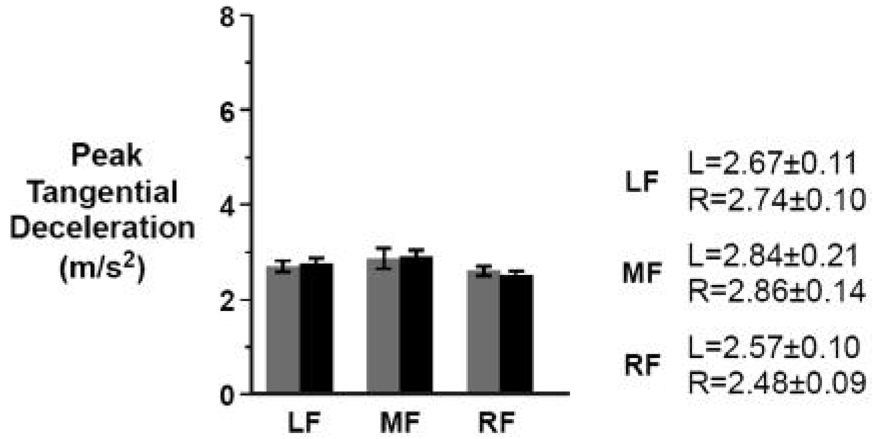

Figure 12. The mean of peak tangential deceleration across target regions in FB condition.

The last dependent measure that was taken into consideration when evaluating sensorimotor performance was the combine joint work (CJW). The CJW is an estimate of the movement efficiency computed as the integral of the product of joint torque and joint velocity. Therefore, both kinematics and kinetics of performed reaching movements were taken into consideration. In Figure 13, we show the interlimb differences in modulation of the CJW across all targets. As expected, the least amount of estimated muscle work was spent when reaching to targets closer to the body. The largest amount of work was spent for the furthest movements into contralateral hemispace. For example, when reaching to the top right target with the left hand the CJW was on average 3.31 Nm·rad/s^2. Although the right hand yielded a similar pattern, the CJW was found to be substantially smaller as being 2.63 Nm·rad/s^2 when reaching to the top left target that qualified to the LF region based on reaching frequency. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F_{(2,332)}$=135.09, p=.0001) for the CJW. The left hand showed a significant advantage when reaching to the LF region (0.80±0.05 vs. 2.05±0.11 Nm·rad/s^2, p=.0001, Tukey HSD) as shown in Figure 14. This was opposite in the RF region, where the right hand had a significant advantage (0.82±0.06 vs. 1.50±0.06 Nm·rad/s^2, p=.0001, Tukey HSD). In the MF region, where there was no significant effect of hand in reaching frequency, left hand also displayed a significant advantage in terms of CJW being on average 1.11±0.06 and 1.76±0.13 Nm·rad/s^2 for the left and right hand respectively (p=.001, Tukey HSD). Even though there is an advantage of right hand in the RF region, this advantage diminishes on the MF and LF region. However, when we consider the midline of the body in which both hands had the same reaches in terms of distance and direction, right hand spent significantly less energy than left hand in that region (Figure 15). As we mentioned above, right hand advantage in MF region decreases in terms of energetic efficiency. Nevertheless, energetically more efficient reaches with right hand in the midline of the body may lead participants to reach the targets in the contralateral hemisphere next to the midline of the body.

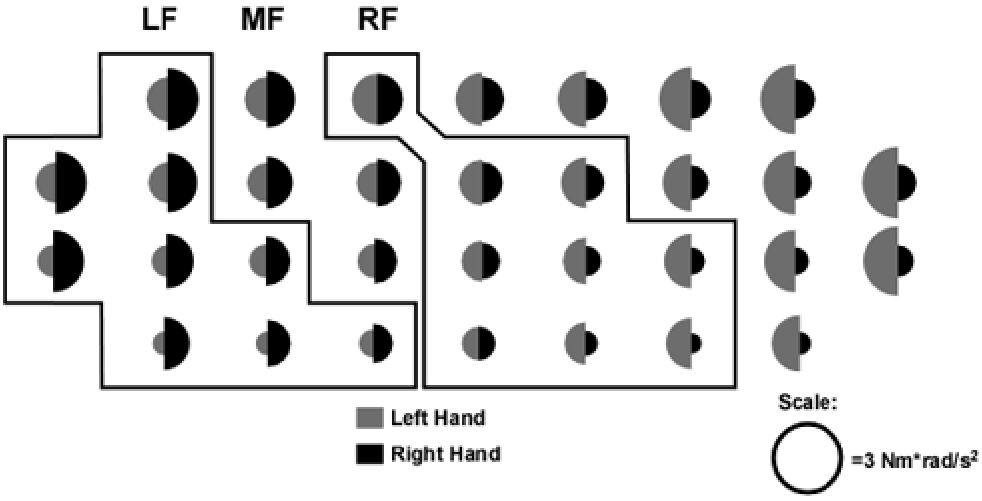

Figure 13. Mushroom plot of CJW between hands with the distribution of all targets averaged across subjects in FB condition.

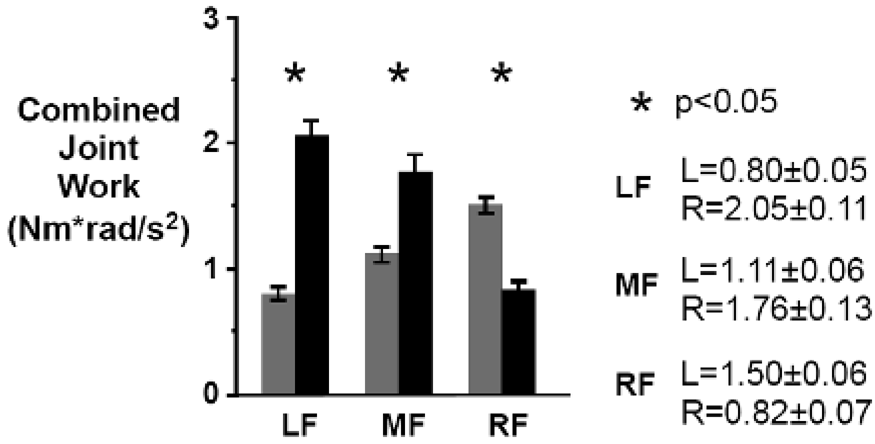

Figure 14. The mean of CJW values across targets regions in FB condition, $p<0.05$.

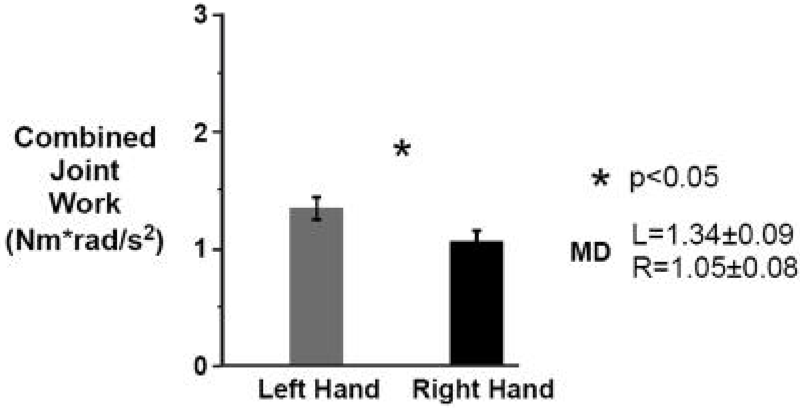

Figure 15. The mean of CJW between hands in the midline of the body (MD), $p<0.05$.

3.6 Discussion

The experiment 1 aimed firstly to find general distribution of the left and right hand reaches in workspace. Moreover, we also tried to find the effect of distance amplitude on those reaches. Our final aim was to find whether limb selection is based on sensorimotor performance asymmetries.

The result of the FB choice of hand condition across all targets showed more significant reaches with right hand than with left hand (68% vs. 32%, respectively). The trend for higher percentage of right hand reaches was also found in previous studies (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003). However, in this experiment, the general percentage of right hand reaches was found to be 68% which is usually higher than what is stated in the literature (approximately 60% reaches with the right hand) (Gabbard & Rabb, 2001; Mamolo et. al, 2004; Stins, Kadar, & Costall, 2001). The possible reason to have higher right hand reaches percentage might be related to the number or the distribution of targets in the workspace. In most of the studies, researchers used only 5 to 7 targets positioned in the arc design distanced at approximately 70%

of arm length. In this experiment, we had 32 targets with 4 lines in transverse plane (horizontal in Figure 1) that were set up at 25, 40, 55 and 70% of the arm length. Therefore, closer locations to the body were also explored and increasing location and number of targets also enhanced the usage of right hand.

We determined three regions (LF, MF,+ & RF) of targets to emphasize spatial division with respect to reaching frequency. The main finding in the choice of hand condition is that the MF group of targets is shifted into the left space. In many studies, it was consistently found that right-handers use their dominant hand to pick up objects on the right hemispace, on the midline, and on the position next to the body midline in the contralateral hemispace (Gabbard, Iteya, & Rabb, 1997; Helbig & Gabbard, 2003; Mamolo et. al, 2004). Therefore, right-handers shift from usage of right hand to left hand in the contralateral hemispace close to body midline. Our result with MF region, as it indicated an equal number of reaches for left and right hands, is in agreement with the previous studies.

As we stated earlier, we also searched the effect of distance amplitude on left and right hands reaches, which was not explored in previous studies. The results of the choice of hand condition displayed a significant effect of target distance amplitude when comparing the shortest with the longest targets in the first two parasagittal planes to the left side from the midline of the body. This means that the usage of right hand increases when the target is located further to the body. Reaching to the further targets requires more extension with shoulder and elbow than reaching to the closer targets. It was earlier stated that the right dominant hand has an advantage in coordinating intersegmental dynamics during reaching (Sainburg & Kalakanis, 2000; Bagesteiro &

Sainburg, 2002; Shabbott & Sainburg, 2008), and this strategy can work better if the reaching requires more extension of shoulder and elbow. Therefore, right hand coordination advantage may lead people to reach further targets with their right hand that was found in this experiment.

The result of the choice of hand condition was similar to result of previous studies in terms of the general distribution of right hand and the location for shifting from right to left hand (MF region). As we mentioned earlier, researchers explained this phenomenon based on theoretical clarifications. In this experiment we had both qualitative and quantitative data to find out the underlying mechanisms of hand preference looking at the interlimb difference. We looked the data from left and right hand forced conditions to make interlimb comparison. We had six dependent variables and we made comparisons considering three regions of interest and hands.

When we look at the result of movement accuracy (FPE) across target regions (LF, MF, & RF) for this reaching task under the visual feedback condition, we did not find interlimb difference. That is, there is no advantage in FPE across both hands and target regions. Moreover, peak tangential velocity did not result in an accuracy difference on target regions. The peak tangential velocity was higher in the LF region for right hand than for left hand and vice versa in the RF region. However, this did not make any interlimb difference between hands in terms of FPE across these target regions. In general, whereas some studies showed better performance for the accuracy of preferred arm under the matching and manual aiming tasks with available visual feedback (Goble & Brown, 2008; Grouios, 2006; Ma-Wyatt & McKee, 2006), other studies showed no significant differences in accuracy (Carson, Chua, Elliott, & Goodman, 1990; Imanaka, Abernethy, Yamauchi, Funase, & Nishihira, 1995). In this experiment, we also did not find an advantage of FPE between hands, which is in agreement with Carson et al. (1990) and Imanaka et al. (1995) studies. Overall, as there was no significant interlimb difference across target regions in terms of FPE, this variable can not explain results of the reaching frequency in the choice of hand condition.

Analysis of the hand path linearity (HPL) data which represents the quality of movement revealed a significant difference between hands for the RF region and no significant difference was found for the MF and LF regions. When reaching to the RF region with left hand, large curvature hand path linearity was shown to be associated with the deficiencies in torque strategies (Bagesterio & Sainburg, 2002). This deficiency may lead people to prefer their right hand to reach to RF region targets. There was no advantage of either hand on the MF region; therefore, this can also explain hand preference behavior. Left hand reaches to the LF region were mainly single joint movements and did not require more shoulder excursions. Therefore, HPL of left hand reaches became less curved in the LF region. However, this was not significantly different than that of right hand reaches. In summary, HPL finding can explain hand preference phenomenon especially in the MF and RF regions.

The peak tangential velocity, acceleration, and deceleration were also calculated across target regions between hands to support information about speed of the movements with the directions and increase and decrease in the magnitude of velocity. Peak tangential velocity varied with movement distance for both hands. That is, left hand reaches were faster to RF region than LF region and it was vice versa for right hand. Even though the same pattern was observed in acceleration profile for right hand reaches, left hand reaches did not show this pattern. Therefore, for the dominant right hand, peak tangential velocity and acceleration varied across target distances and, as such, a good predictor for movement distances. In contrast, for the non-dominant left hand, only peak tangential velocity varied across target distances but not acceleration. Previous research has indicated that the mechanisms responsible for the different movement extents were quite distinct for each arm (Brown & Cooke, 1986; Ghez & Gordon, 1987; Krakauer, Gordon, Veytsman, & Ghez, 2002; Sainburg & Schaefer, 2004). Our current findings support this idea by showing that each arm system relies different processes to specify movement distance. Peak tangential deceleration did not vary across target regions between hands. Thus, it is not a good predictor of movement distance.

The analysis of the modulation of the movement efficiency defined by the CJW displayed a significant difference between hands on the RF region. The less amount of estimated muscle work was spent when reaching to targets located on the RF region by right hand. On the MF and LF regions, that was in favor of left hand. That is, left hand reaches to the MF and LF reaches were more efficient than right hand reaches. In fact, this result is not surprising especially for the MF region because all the MF region targets are located on the left hemispace. All those four targets are in proximal distance to left hand. Thus, left hand reaches could be performed with spending less muscle work than right hand reaches in the MF region. However, when we looked at the targets located in the midline of the body where both hands traveled the same distance and direction, right hand spent less energy than left hand (Figure 15). Thus, more efficient movements with right hand in the midline of the body may direct participants to use their right hand in the left hemisphere close to the midline of the body.

In summary, we found no interlimb differences in FPE across target regions but significant interlimb differences in HPL (RF region) and CJW (LF, MF, & RF regions). Therefore, the FPE cannot explain results of the reaching frequency in the choice of hand condition. However, the results of the HPL together with the CJW corresponded well to the hand selection. This suggests that the choice of hand is more likely to be an active decision based on evaluation of quality and energetic efficiency of the movements. Putting together all the results obtained here, we are led to believe that, the interlimb differences in sensorimotor performance associated with handedness dictate the hand selection in our reaching task.

CHAPTER 4

EXPERIMENT 2

4.1 Introduction

In our first experiment, we have found that the choice of hand under the visual feedback condition is more likely to be based on evaluation of quality and energetic efficiency of the movements. This is associated with the interlimb differences that drive people to choose their right dominant hand even in the contralateral hemispace next to the body midline. Thus, less efficient movements to the body midline and neighboring areas with non-dominant hand under visual feedback condition lead people to choose dominant hand to those regions. Taken together with the results of the first experiment, it seems reasonable to conclude that hand preference depends on interlimb differences associated with the sensorimotor performance, in this case visual feedback.

There has been increasing attention over the past several decades in the role that sensory feedback might play in determining arm performance asymmetries. In fact, this idea has been supported with some studies (Bagesterio & Sainburg, 2002; Goble & Brown, 2008; Wang & Sainburg, 2006). These studies suggested that performance differences might also be related to asymmetries in visual or proprioceptive processing. Despite the evidence that electrical stimulation of afferent proprioceptive pathways elicit a similar response for the left and right arms (Aimonetti, Morin, Schmied, Vedel, & Pagni, 1999), it has typically been shown that right-handed subjects perform proprioceptive target matching tasks with greater accuracy when using the non-dominant left thumb (Nishizawa, 1991) or elbow (Goble, Hurvitz, & Brown, 2006; Goble & Brown, 2007). For instance, Goble and Brown (2008) have found non-dominant hand advantage during proprioceptive target matching but dominant hand advantage during visually determined target matching. In another study, Lenhard and Hoffmann (2007) have found that left hand performance was better for the final position accuracy during unimanual aiming task without visual feedback. These suggest a left arm/right hemisphere specialization for the utilization of proprioceptive feedback, which may be related to general use of the non-dominant arm for proprioception-based object stabilization tasks. This is particularly appropriate in the context of bimanual activities, in which vision is often diverted to the dominant arm for object manipulation. The dominant hand selection bias under the visual feedback condition has been associated with the more efficient reaches made by the dominant hand. However, the result of the studies stated above gives rise to idea that sensory information related to the task can play an important role on task performance. Therefore, in the second experiment, we asked whether limb selection is affected by sensorimotor information; lack of visual feedback. In another way, whether the right hand bias in the hand selection behavior is associated with the life-time habit or it is an active choice because of the more efficient reaches.

4.2 The Purpose of the Study

Motor performance asymmetries between hands led people to use their dominant hand more than non-dominant hand during reaching when visual feedback was available. However, some studies showed that motor performance asymmetries could be also related to the sensorimotor information. In the experiment 2, we aimed to find whether occlusion of visual feedback affects sensorimotor performance asymmetries, thus, limb selection behavior.

4.3 The Hypotheses

1. Based on previous findings, right hand reaching frequency will be overall more than that of left hand.
2. There will be an effect of distance amplitude on hand preference.
3. Occlusion of visual feedback will influence hand selection for reaching tasks.
4. Left and right hands' performances will be significantly different in terms of FPE, HPL, and CJW during the reaching movements.

4.4 Materials and Methods

4.4.1 Participants

Twenty-four participants (12 females and 12 males) aged between 18-32 years old (M_{age}=25.2, SD=4.2) signed the consent form approved by the Institutional Review Board of the Pennsylvania State University. Participants were voluntarily enrolled in this study. To meet the requirements of the study, participants had to be healthy with a sedentary life style that had no regular sports backgrounds. All participants were strongly right-handed with scores >95% on the 12 item Edinburgh Inventory (Oldfield, 1971). They were grouped with respect to experimental design in a pseudo-randomized manner to make sure that the gender was equally represented in each testing condition. The exact nature of the experiment aim was explained to each voluntary participant. Everybody was paid minimum wage for his or her participation.

4.4.2 Experimental Setup

The Experimental setup was the same that was used in the experiment 1 (Figure 1).

4.4.3 Experimental Design

In the experiment 2, the visual feedback of the cursor representing the tip of the index finger was not provided (NFB). Thus, in the NFB condition participant did not see the cursor during the movement but they could see just between the trails. The same with the experiment 1, experiment 2 consisted of three conditions: choice of hand, forced right- and forced left-hand reaching movements to targets positioned across the frontal workspace. Whereas the choice of hand condition tested frequency of selected hand, the forced hand conditions provided equal data sample for both hands to examine movement accuracy, quality and efficiency.

The rest of the experimental design was the same with the experiment 1.

4.4.4 Experimental Task

The same experimental task was used like in the experiment 1. Only difference was that feedback about the performed cursor path was not provided to the participants.

4.4.5 Data Analysis

For the data analysis, we have followed the same procedures that we had done in the experiment 1. Initially, three regions of interest were identified in the frontal workspace in the NFB experiment. In these areas of interest (Figure 16) but in the forced hand conditions, six dependent variables that depict sensorimotor performance were quantified across subjects.

The statistical analysis was performed using two-way repeated measures ANOVA with subject being a random factor. This analysis was based on hand (2) by target (32) interaction for the reaching frequency and on hand (2) by regions of targets (3) interaction for other six dependent variables. Post-hoc analysis was performed using Tukey HSD (Honestly Significant Difference) test. The level of significance was set to $p<0.05$ and was computed using JMP 8.0 statistical package (SAS Institute, USA).

4.5 Results

In response to the change of the sensorimotor information during our reaching task in the NFB choice of hand condition, participants modulated reaching frequency accordingly to our predictions. In Figure 17, we show that the difference between hands in reaching frequency averaged across all targets and subjects decreased being 60 and 40% for the right and the left hand respectively (68% vs. 32% in the FB condition). The repeated measures ANOVA showed a significant 2-way interaction (2x32) between hand (L & R) and target (1-32) ($F_{(31,441)}=267.17$, $p=.0001$). In Figure 16, we indicate the distribution of reaching frequency between hands across all targets. As in the FB condition, our approach was to qualify all targets reached significantly more with the left hand to the LF group. The RF group consisted of analogous symmetrical targets to the right side from the MF group, which was formed by targets that showed no significant difference between hands. In the NFB condition, we found only one target with no significant difference between hands (mean difference=5%, $p=.96$, Tukey HSD) that formed the MF group as outlined in Figure 16. The LF group included 13 targets that were reached using the left hand with frequency above 68% (p=.001, Tukey HSD). The RF targets were reached using the right hand with the frequency above 88% (p=.0001, Tukey HSD). Similarly to the FB condition, we found a significant effect of the distance amplitude on the reaching frequency when considering the shortest and the furthest target in the first parasagittal plane to the left from the midline of the body (p=.0001, Tukey HSD). The right hand usage increased from 4.5±2.2% for the shortest target to 52.9±7.8% for the furthest one. Although not significant (p=.99, Tukey HSD), similar trend was observed in the second parasagittal plane further to the left side, where the right hand usage increased from 1.3±1.3% to 13.8±6.0% respectively. The main finding here is that occlusion of the visual feedback led to a change in the distribution of reaching frequency with the left hand being employed on average more frequently in comparison to the FB condition. The transition area for switching hand selection became much smaller (MF=1 target) and was shifted to the right side being now closer to the midline of the body.

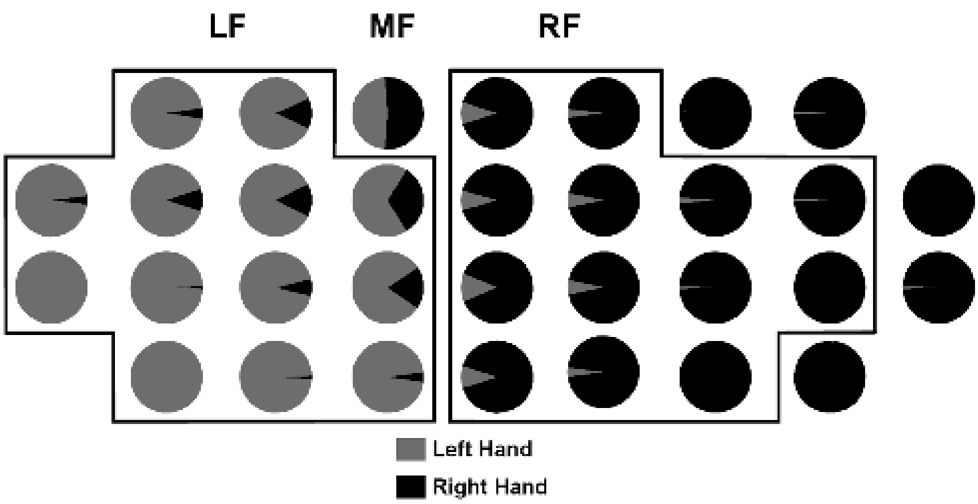

Figure 16. Pie chart of reaching frequency between hands with the distribution of all targets averaged across subjects in NFB condition.

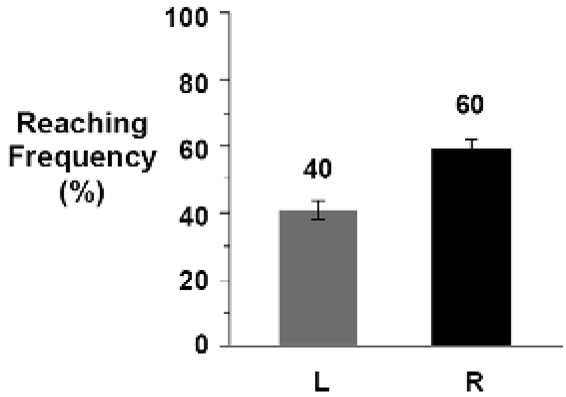

Figure 17. Mean of reaching frequency between hands across all targets and subjects in NFB condition.

In order to explain this behavior, our three dependent variables that determined accuracy (FPE), quality (HPL) and efficiency (CJW) of the movement were subjected to repeated measures ANOVA. In addition, three more dependent variables were (tangential velocity, acceleration, and deceleration) analyzed to support information about speed of the movements with the directions and increase and decrease in the magnitude of velocity. For this purpose, another 2 groups of subjects (see Methods) performed the same reaching task in the NFB condition being forced to use either the left or the right hand. Like for the FB, the dependent measures were collapsed across our three groups of targets (LF, MF & RF) identified based on the reaching frequency.

In Figure 18, we show the distribution of the FPE that defines movement accuracy. As expected, the FPE was found to be much higher in the NFB in comparison to the FB condition and ranged between 0.019±0.002 and 0.037±0.004 across hands and targets. The mean value across targets was 0.030±0.0006 and 0.023±0.0004 m for the right and left hand respectively. In contrast to the FB condition, the repeated measures ANOVA in the NFB condition showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F_{(2,412)}$=5.8, p=.02). Furthermore, our post hoc analysis revealed a significant advantage of the left hand in both the LF (p=.0001, Tukey HSD) and the RF (p=.001, Tukey HSD) regions as shown in Figure 19. Although not significant (p=.56, Tukey HSD), a slight advantage of the left hand in the MF region was also present. In this case, a lack of significance level was due to the fact that only one target qualified to the MF group in the NFB condition as outlined in Figure 18. Overall, our results of movement accuracy under the NFB condition display a substantial disadvantage for both hands in comparison with the FB condition. However, the movement accuracy of the right hand under the NFB condition is affected considerably more than that of the left hand. Therefore, there is a clear advantage of the left hand across all target regions, which is consistent with previous findings reported in the literature (Goble, Hurvitz, & Brown, 2006; Goble & Brown, 2008; Lenhard & Hoffmann, 2007; Wang & Sainburg, 2006). Similarly to the FB condition, the pattern of movement accuracy results did not seem to reflect hand selection behavior.

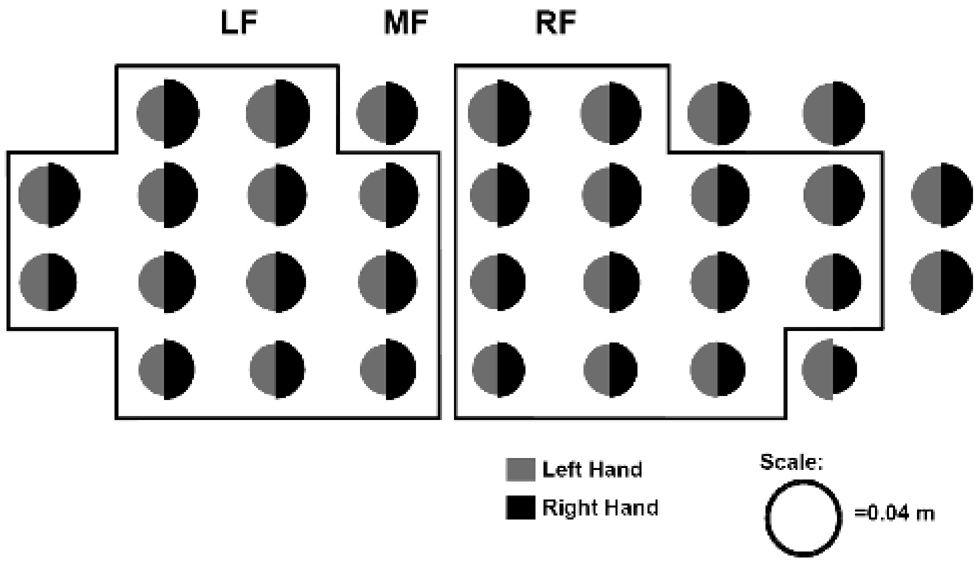

Figure 18. Mushroom plot of FPE between hands with the distribution of all targets averaged across subjects in NFB condition.

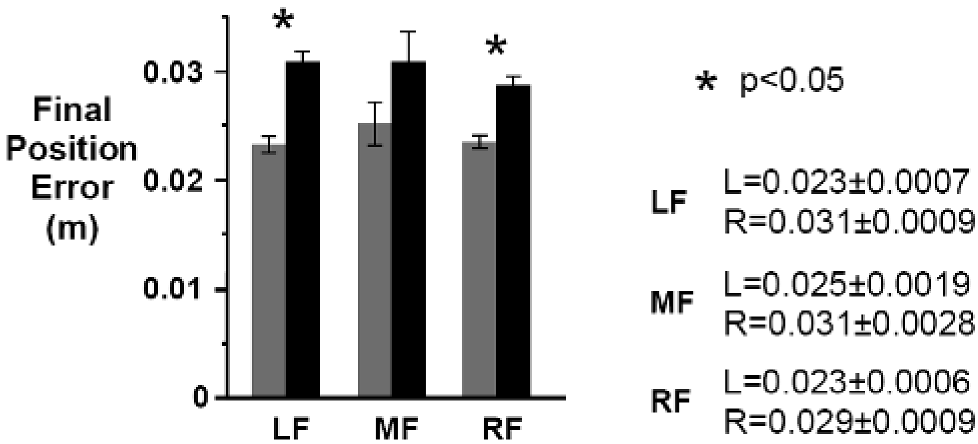

Figure 19. The mean of FPE values across targets regions in NFB condition.

In Figure 20, we show the averaged results of the HPL measure for all targets in the NFB condition. Similarly to the FB condition, subjects performed the most curved movements to the shortest targets in the center region and the least curved movements to the ipsilateral side. The main difference is that under the NFB condition both left and right hand performed the least curved movements to the ipsilateral side. This was not the case under the FB condition in which only the right hand showed that pattern. Overall, the HPL ranged the same way across both conditions (0.03-0.08). The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}$=10.05, p=.0001). Figure 21 shows the average HPL across subjects and regions of interest. In the MF region, the HPL measures were 0.055±0.007 and 0.057±0.008 for the right and left hand respectively, which was not significant (p=.99, Tukey HSD) as it was the case in the FB condition. Note that the HPL in the NFB condition was smaller when compared to the FB condition for MF region (Figure 21 vs. Figure 8) but the reduced number of targets could possibly explain this difference. Unlike to the FB condition, the left hand showed a significant advantage in the LF region as shown in Figure 21 (p=.009, Tukey HSD). Whereas the left hand performance improved substantially in the LF region for the NFB condition (0.055 vs. 0.063), the right hand showed no change (0.064 vs. 0.065). In the RF region, a relatively similar improvement of the left hand curvature was found (0.064 vs. 0.076). Although right hand showed no change in that region (0.057 vs. 0.060) as shown in Figure 21, its advantage was found to be significant (p=.04, Tukey HSD) as it was the case in the FB condition (see Figure 8). Overall, the left hand improved its performance in absolute terms when the visual feedback was removed and the right hand performance did not change. It is important to realize that under the NFB condition, these movement curvature results reflect the pattern of hand selection across all regions.

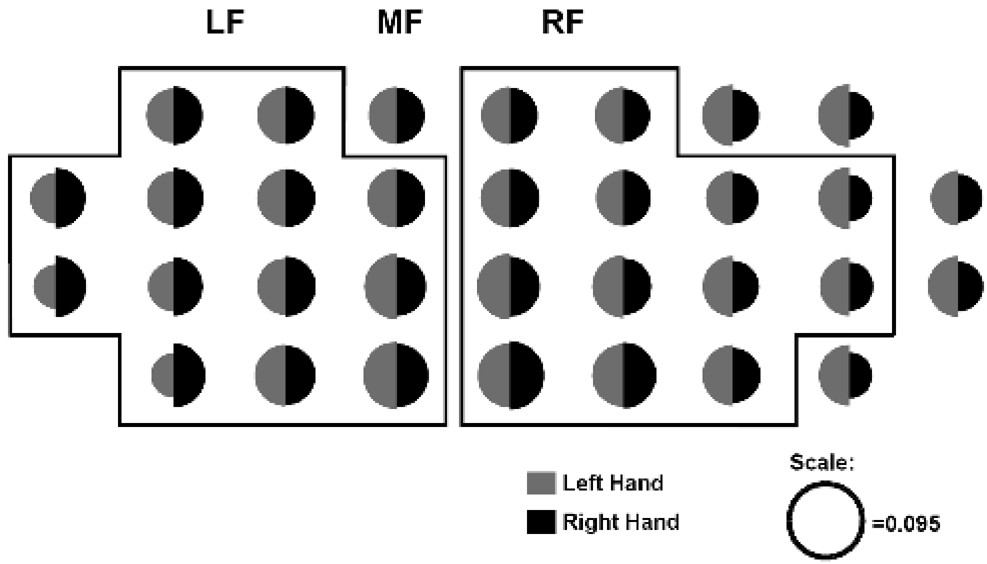

Figure 20. Mushroom plot of HPL between hands with the distribution of all targets averaged across subjects in NFB condition.

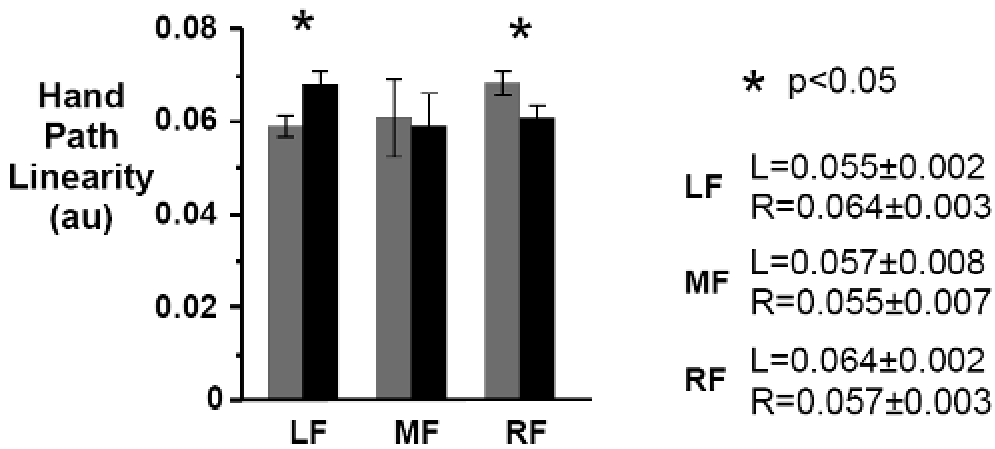

Figure 21. The mean of HPL values across targets regions in NFB condition, $p<0.05$.

The tangential velocity profile of left and right hand reaches in three target regions was shown in Figure 22. Please note that we had a requirement for the completion of trials. The peak tangential velocity showed the same trend toward faster movements when reaching to contralateral hemispace with either hand as was observed in the FB condition. We can see in Figure 22 that left hand reaches are faster than right hand reaches in the RF region but slower in the MF and LF regions. On the contrary, right hand reaches are substantially faster in the MF and LF regions. Statistical analysis showed the similar results. The repeated measures ANOVA displayed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}$=50.07, p=.0001) for the velocity. Left hand reaches were significantly faster than right hand reaches in the RF region (0.58 m/s vs. 0.53 m/s, p=.03, Tukey HSD). In the MF region, even though right hand reaches were faster than left hand reaches, that was not found to be significantly different (0.71 m/s vs. 0.68 m/s, p=.97, Tukey HSD). Opposite to the RF region, right hand showed significantly faster reaches than left hand reaches in the LF region (0.68 m/s vs. 0.52 m/s, p=.0001, Tukey HSD). Note that velocity is substantially higher for both hands in the MF region because MF region included only one target that is located on the line furthest from the body. Overall, each hand moved faster to the contralateral hemispace to accomplish the task in a given time in the NFB condition which was also the case in the FB condition.

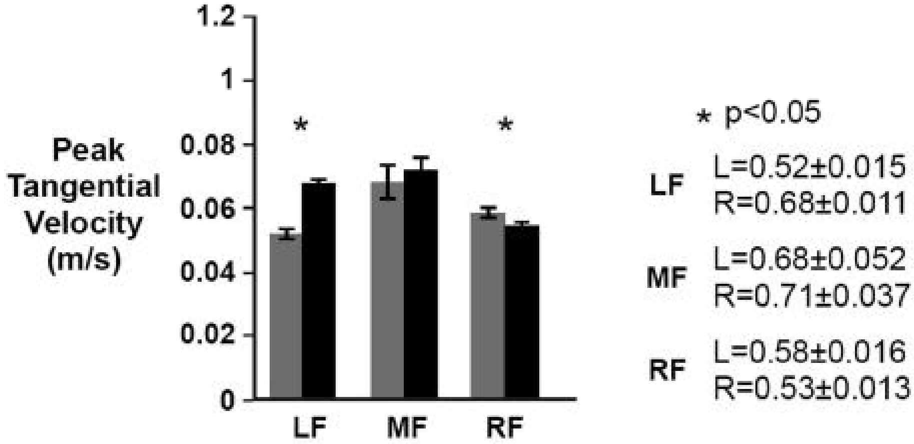

Figure 22. The mean of peak tangential velocity across target regions in the NFB condition, $p<0.05$.

The peak tangential acceleration profiles of left and right hand reaches in three regions were displayed in Figure 23. Tangential acceleration profiles in the NFB condition showed similar trend as was observed in the FB condition. Even though slightly higher acceleration for right hand is apparent in MF region, it becomes very similar to the left hand in RF region. As we may expect, acceleration is higher in LF regions for right hand than left hand. Statistical analysis of repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}=12.59$, $p=.0001$) for acceleration. Post-hoc analysis revealed that acceleration is significantly higher for right hand than for left hand in LF region (3.82 m/s^2 vs. 3.35 m/s^2, $p=.0001$, Tukey HSD). However, there was no significant difference in MF (left hand: 3.72 m/s^2 and right hand: 3.86 m/s^2, $p=.99$) and RF regions between hands (left hand: 3.32 m/s^2 and right hand: 3.26 m/s^2, $p=.96$). Similar to the FB condition, left and right hands' accelerations in the NFB condition were the same in the RF region in spite of the faster reaches with left hand to that region. In addition, right hand acceleration in the NFB condition was found to be faster in LF region which was consistent with the velocity profile and this was also the case in the FB condition.

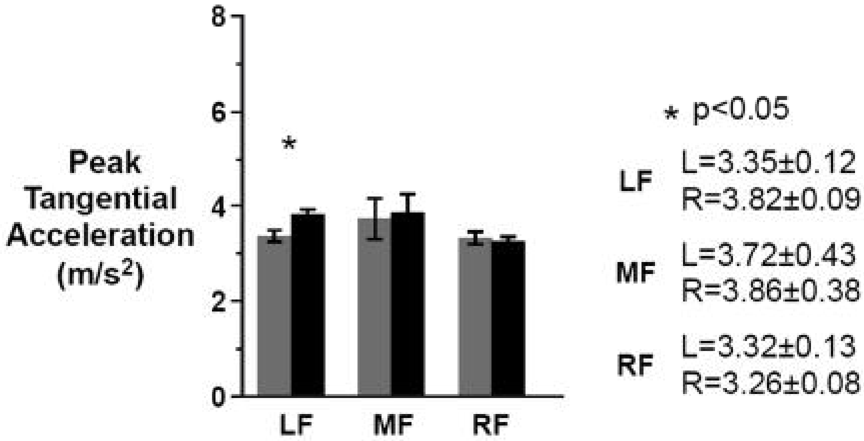

Figure 23. The mean of peak tangential acceleration across target regions in the NFB condition, $p<0.05$.

The deceleration profile of both hands in three regions was shown in Figure 24. The max tangential deceleration looks very similar for both hands in RF and MF regions but not for LF region. In the LF region, right hand shows higher deceleration profile than that of left hand. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hands (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}$=2.95, p=.05) for deceleration. Post-hoc analysis revealed that deceleration is significantly higher for right hand than for left hand in LF region (3.15 m/s^2 vs. 2.78 m/s^2, p=.0001, Tukey HSD). In the NFB condition, faster velocity for right hand than for left hand in LF region is followed with higher acceleration and deceleration in that region.

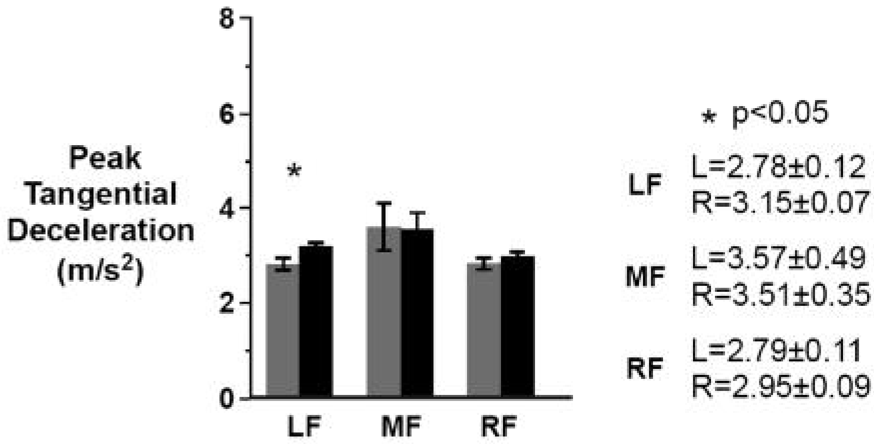

Figure 24. The mean of peak tangential deceleration across target regions in the NFB condition, $p<0.05$.

In Figure 25, we show the distribution of the CJW across the workspace for both left and right hand. As expected and similarly to the FB condition, the least amount of estimated muscle work was spent when reaching to targets closer to the body and the largest amount of work was spent for the furthest movements into contralateral hemispace. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}=265.88$, p=.0001). In Figure 26, the left hand showed a significant advantage when reaching to the LF region (0.93±0.04 vs. 2.28±0.07 Nm·rad/s^2, p=.0001, Tukey HSD). This was opposite in the RF region, where the right hand had a significant advantage (0.95±0.04 vs. 1.91±0.08 Nm·rad/s^2, p=.0001, Tukey HSD). In the MF region, where there was no significant effect of hand in reaching frequency, the CJW was also found to be not significantly different being on average 1.74±0.17 and 1.92±0.23 Nm·rad/s^2 for the left and right hand respectively (p=.99, Tukey HSD). Note that the CJW is substantially higher for both hands in the MF region in the NFB condition (Figure 26 vs. Figure 14). This is due to the fact that the MF region included only one target that is located on the line furthest from the body (see Figure 25). Remember that in the FB condition, the MF region included three more targets that were in similar direction but closer proximity to the body thus required less amount of the CJW to be reached (see Figure 13). Overall, both the right and the left hand showed an increase in the CJW for all regions under the NFB condition. Since this increase was fairly leveled across both hands, the pattern of the CJW results remained the same. Therefore, the CJW seem to reflect the hand selection behavior under the NFB condition, as it was the case under the FB condition.

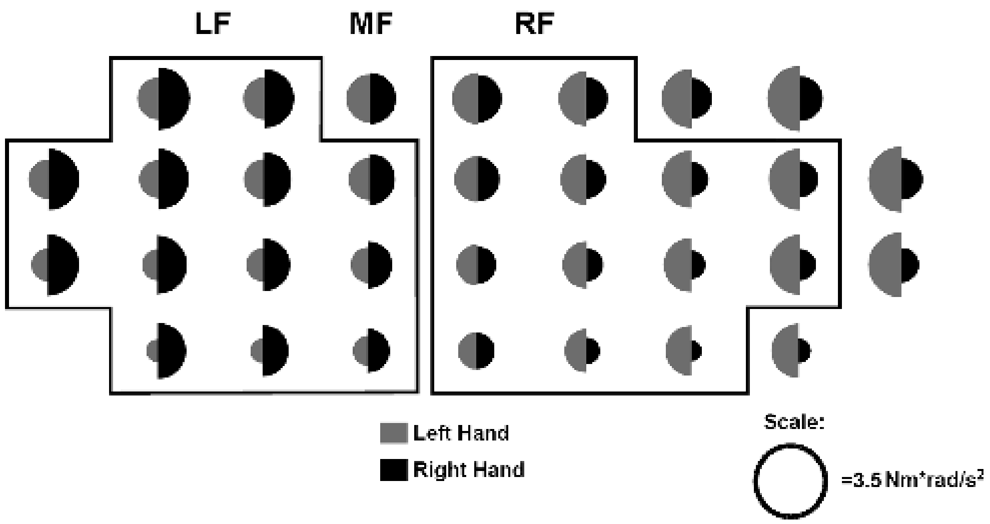

Figure 25. Mushroom plot of CJW between hands with the distribution of all targets averaged across subjects in NFB condition.

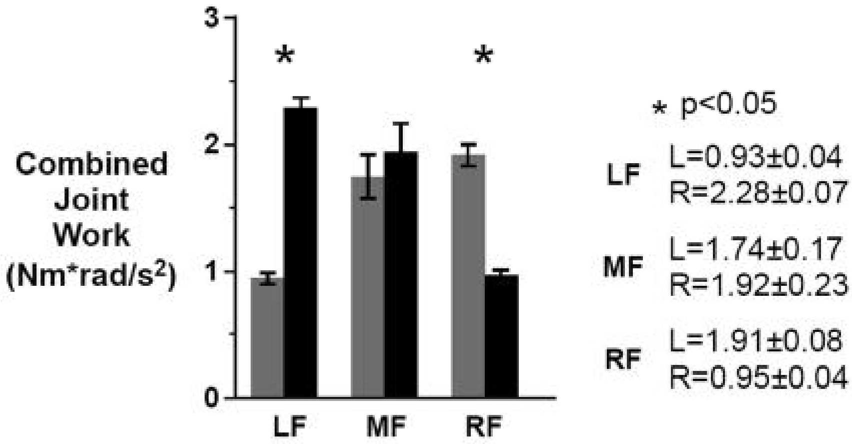

Figure 26. The mean of CJW values across targets regions in NFB condition, $p<0.05$.

4.6 Discussion

The experiment 2 aimed firstly to find general distribution of the left and right hand reaches in workspace when there is no available visual feedback with moving hand. The result of the experiment 1 showed more right hand reaches in the hand selection task. In the experiment 2, we asked whether the right hand bias in the hand selection behavior in the experiment 1 is associated with the life-time habit or it is an active choice because of the more efficient reaches. Similarly to the experiment 1, we also tried to find the effect of distance amplitude on those reaches. Finally, we aimed to find whether limb selection under the NFB condition is based on sensorimotor performance asymmetries.

Similarly to the FB condition and to the previous studies (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003), the result of the NFB choice of hand condition across all targets also showed more significant reaches with right hand than with left hand (60 vs. 40%, respectively). However, the percentage of left hand reaches increased 8% from the FB condition to the NFB condition. Therefore, when people have only proprioceptive sensory information, they tend to prefer their left hand more than when they have both visual and proprioceptive information. The more left hand usage in the NFB condition resulted with change of the transition area for switching hand selection. This transition area consisted of only one target in the NFB condition and was shifted to the right side being closer to the midline of the body. Thus, the main finding in the NFB condition is that the distribution of reaching frequency was changed with the more frequently usage of left hand in comparison to the FB condition.

In accordance with the FB condition, we found a significant effect of the distance amplitude on the reaching frequency when considering the shortest and the furthest target in the first parasagittal plane to the left from the midline of the body. Similar trend was also observed in the second parasagittal plane further to the left side but it did not reach the significant level. Thus, occlusion of visual feedback did not affect the distribution of distance amplitude on the reaching frequency. That is, the usage of right hand increases when the target is located further to the body. As we concluded in the FB condition, right hand advantage in coordinating intersegmental dynamics during reaching (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002; Shabbott & Sainburg, 2008) may lead people to reach farther targets with their right dominant hand regardless of the visual feedback.

In order to explain this hand selection behavior in the NFB condition, we had also forced conditions where we asked participants to reach with either left or right hand. The data from the forced conditions gave us information if the change in the hand section behavior under the NFB condition was caused by the change in the interlimb difference. We had six dependent variables and we made comparisons considering three regions of interest and hands.

The result of movement accuracy (FPE) across target regions (LF, MF, & RF) for reaching task under the NFB condition displayed a significant interaction. This was not the case in the FB condition in which there were no hand advantages in terms of FPE. In the NFB condition, where there was only proprioceptive information about the moving hand, left hand showed remarkable advantage across all regions. Besides, FPE was not affected by peak tangential velocity. For instance, even though left hand reaches were faster in RF region and vice versa in LF region, accuracy was found to be better for left hand in both regions. Therefore, the ability to produce better accuracy for left hand can be explained by the more effective usage of the proprioceptive information under the NFB condition. In fact, many studies have shown non-dominant left hand superiority for the final position accuracy during target matching and aiming tasks when there is no available visual feedback (Bagesteiro & Sainburg, 2002; Goble & Brown, 2008; Guiard, Diaz, & Beaubaton, 1983; Lenhard & Hoffmann, 2007; Sainburg, 2002; Sainburg & Wang, 2002). The result of FPE in the experiment 2 is parallel with the previous studies. Moreover, we have also found that left hand performed better accuracy regardless of the velocity and target regions. Overall, as there was substantial left hand advantage in terms of FPE across all regions in the NFB condition, this variable cannot explain results of the reaching frequency in the choice of hand condition. This was also the case in the FB condition.

Analysis of the hand path linearity (HPL) data which represents the quality of movement revealed a significant interaction between hands and target regions. The result of this analysis showed that both hands displayed straighter reaching movements to their ipsilateral hemispheres. That is, left hand showed less curvature hand path linearity in LF region and right hand showed less curvature hand path linearity in RF region. However, there was neither hand advantage in

MF region in terms of HPL. In fact, this interlimb difference between hands in HPL perfectly reflects hand selection behavior in the NFB condition. In comparison to the FB condition, left hand showed less curvature hand path linearity under the NFB condition. However, right hand HPL to three target regions stayed almost the same under both FB and NFB condition. It has been previously shown that non-dominant left arm is specialized in sensory feedback mediated error correction mechanism in a load compensation task (Bagesteiro & Sainburg, 2003). The reason of having less curvature hand path linearity for left hand under the NFB condition than FB condition may be related to the more efficient usage of proprioceptive sensory feedback which was stated by earlier work of Bagesteiro and Sainburg (2002). In general, the result of HPL can explain hand selection behavior across all regions under the NFB condition.

In order to provide information about the speed of the reaching movements with the directions and increase and decrease in the magnitude of velocity, we calculated peak tangential velocity, acceleration, and deceleration across target regions between hands. Similarly to the FB condition, peak tangential velocity varied with movement distance for both hands in the NFB condition. Moreover, acceleration profile of left and right hand in the NFB condition was the same as the FB condition. Whereas right hand peak acceleration was higher in LF region, left hand peak acceleration was found to be similar to that of right hand in RF region. Thus, peak velocity and acceleration of right hand reaches varied across target distances and can be viewed as a good predictor for movement distances which was also found in previous studies (Brown & Cooke, 1986; Ghez & Gordon, 1987; Krakauer, Gordon, Veytsman, & Ghez, 2002; Sainburg & Schaefer, 2004). However, only peak velocity of left hand varied across target distances but not acceleration. Therefore, our conclusion in the experiment 1 is also valid in the experiment 2. This result shows that occlusion of visual feedback do not change the mechanism responsible for the specifying movement distance. Higher peak tangential velocity and acceleration in LF region for right hand than for left hand in the NFB condition was followed with higher deceleration for right hand in that region. This pattern was not observed in the FB condition.

The result of the CJW displayed a significant interaction between hands and three target regions. The further analysis revealed that right hand spent less amount of estimated muscle work than left hand when reaching to the targets located on RF region. However, this trend was opposite in the LF region where left hand spent less amount of estimated muscle work than right hand. On the MF region where there was same amount of left and right hand reaches, CJW was also found to be similar. Note that the switch from right to left hand in limb selection occurred after passing MF region further to the left hemisphere. The result of the CJW also shows that left hand spends less energy after passing this transition area. Thus, similar to the HPL, CJW explains the hand selection behavior across all regions.

In summary, we found a substantial left hand advantage in terms of FPE across all target regions, which has been also shown in previous studies (Bagesteiro & Sainburg, 2002; Goble & Brown, 2008; Guiard, Diaz, & Beaubaton, 1983; Lenhard & Hoffmann, 2007; Sainburg, 2002; Sainburg & Wang, 2002). If hand selection depends on the asymmetries in FPE, you might expect to see better accuracy for right hand especially on RF region. As this was not the case in the NFB condition, FPE cannot explain result of the reaching frequency in the choice of hand condition. However, significant interactions between hands and target regions were found in HPL and CJW. The results displayed that left hand reaches to LF region were more efficient than right hand reaches in terms of

HPL and CJW. On the contrary, right hand reaches to RF region were found to be more efficient than left hand reaches in terms of HPL and CJW. In addition, there were no hand advantages in MF region in terms of quality and energetic efficiency. Therefore, the results of the HPL together with the CJW corresponded well to the hand selection. Note that, the same variables explained the hand selection behavior in the FB condition. In the experiment 2 where visual feedback was removed during the reaching movements, the pattern of hand selection was also changed. This change was well explained by the change in HPL and CJW. If the same distribution of right hand reaching frequency in the FB condition in hand selection were also seen in the NFB condition, we would conclude that hand selection is a life time habit. However, the result in the NFB condition led us to suggest that the choice of hand is more likely to be an active decision based on evaluation of quality and energetic efficiency of the movements rather than a life time habit. In conclusion, the change of interlimb difference from the FB condition to the NFB condition is also resulted with the change of hand selection behavior, which in turn, implies that the interlimb differences in sensorimotor performance associated with handedness dictate the hand selection.

CHAPTER 5

EXPERIMENT 3

5.1 Introduction

It has been previously reported that task and context play an important role to prefer a hand to execute a reaching movement (Gabbard & Helbig, 2004). In our first and second experiments we have shown that hand preference mainly depends on motor performance asymmetries between hands. In addition, we have also explored that sensory information about the moving hand also influences motor performance asymmetries, thus, hand preference.

The results of the two experiments are associated with *dynamic dominance hypothesis*, which suggests that dominant arm is specialized for controlling limb trajectory, whereas non-dominant arm appears to be specialized for controlling limb position or impedance and has superiority for somatosensory-based feedback-mediated control. Other research has also suggested that hand preference can be influenced through intensive practical training (Mikheev, Mohrb, Afanasiev, Landis, & Thut, 2002). In line with this proposition, some researchers reported that motor preferences as well as the cortical representations of body are not predetermined entities, but can be adaptable through experience, for instance sport or musical practice (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Mikheev et al., 2002). Mikheev et al. (2002) investigated motor lateralization profiles associated long-term motor training between proficient judo sportsmen and controls through the assessment of a number of handedness items. Their result indicated that athletes prefer to perform certain motor tasks more frequently with the left hand than non-athletes, although overall right-handed. This finding suggests that extensive practice is able to shift hand preference for particular motor tasks in right-handers. However, it is still noteworthy to think that movements in judo involve mainly bimanual coordination and actions. Thus, one might expect to see higher rate of left hand preference in some motor tasks for judo sportsmen because of the usage of bimanual movements in their practice regime. Previous research has also reported that unimanual practice requiring sequential finger movements of the non-dominant left hand induced a persistent shift of hand preference for this task being preferred more frequently by left hand (Teixeira & Teixeira, 2007; Teixeira & Okazaki, 2007). In these studies, however, shift of hand preference seem to be due to extensive practices with the non-dominant left hand which modulates previous tendencies of use of the hands. The similar finding was also observed in monkeys. In a study, researchers initially assessed preferences of monkeys for reaching, and the animals practiced the reaching task (reaching for food) using only their non-preferred hand. The results displayed a noticeable shift of hand preference following non-preferred hand training, with being performed primarily by the originally non-preferred hand (Deuel & Dunlop, 1980). The results of these studies give rise to idea that extensive practice of non-dominant hand on a task can cause shift of hand preference on performing that task. Similar to general hand preference studies, however, studies conducted to find effect of practice on hand preference are limited with qualitative data and focused on only the practiced task. In this final experiment, therefore, we examined the hypothesis that long term patterns of practice should influence limb selection choices. This hypothesis is based on the idea that elite athletic performance should alter movement proficiencies with both hands. According to our hypothesis, we predict that the pattern of hand selection in elite athletes should be different, as a group, than that of non-athletes. In fact, using a questionnaire, Mikheev et al. (2002) found a higher rate of left non-dominant hand preference among proficient judo sportsmen than controls for some items being asked in the questionnaire. It is still worth nothing that this sport involves performing the movements bimanually. Thus, this may lead to increase relative proficiency of both hands. In our final experiment, we compared limb selection patterns of elite fencers and non-athletes (experiment 1). Fencing was chosen as an activity that challenges upper limb coordination quite extensively and focuses predominant, although not exclusively on dominant arm performance.

Fencing is an open-skill combat sport in which two athletes fight indirectly, through their weapons (the foil, the sabre, and the épée), and mainly includes fast pointing movements towards the opponent (Roi & Bianchedi, 2008; Yiou & Do, 2001). As we stated above, it includes mainly unimanual movements and less bimanual coordination. Even though fencers predominantly use their dominant arm to touch the opponent through their weapons, they also use their non-dominant arm to be on the balance during the on-guarde position and the attack (Roi & Bianchedi, 2008). In our final experiment, we aimed to examine if long term patterns of practice influences limb selection. It was previously reported that bimanually performed long term training can change the pattern of hand preference; thus, we hypothesize that elite athletic activity should influence hand preference. In fact, we can predict that extensive practice with the dominant arm should increase dominant arm selection compared to non-athletes. This prediction is based on the idea that all the pointing movements are made by dominant arm in fencing. To test this hypothesis, we implemented a task requiring reaching a target with either hand which is the same as experiment 1. In addition, we compared limb selection patterns in elite fencers and non-athletes and explored the underlying mechanism that causes this pattern. Moreover, we also calculated the effect of target amplitude on limb selection during reaching.

5.2 The Purpose of the Study

It has been previously shown that hand preference can be also influenced by external factors, namely long term training. However, researchers suggested this proposition by focusing only on a sport requiring mainly bimanual coordination of both arms and based on some items from a questionnaire. In this experiment, we aimed to explore if the long term patterns of practice with predominantly by dominant hand influences limb selection and the underlying mechanism of this behavior. In addition, we also aimed to find if the pattern of hand selection behavior is different between elite athletes and non-athletes.

5.3 The Hypotheses

1. Reaching frequency of elite athletes will be different between hands.
2. Reaching frequency will be different between elite athletes and non-athletes.
3. There will be an effect of distance amplitude on hand preference.
4. Left and right hands' performances will be significantly different in terms of FPE, HPL, and CJW during the reaching movements.

5.4 Materials and Methods

5.4.1 Participants

Sixteen elite fencers (8 females & 8 males) aged between 18-24 years old (M_{age}=21.3, SD=2.4) signed the consent form approved by the Institutional Review Board of the Pennsylvania State University. Fencers were voluntarily enrolled in this study. The task requires using sensory information efficiently with the arms; therefore, fencers were asked if they have had any injuries on their upper limbs in the past and none of them had any kind of injuries. Their fencing experiences were changing from 5 to 14 years. All fencers were right-handed with scores >95% on the 12 item Edinburgh Inventory (Oldfield, 1971). They were grouped with respect to experimental design in a pseudo-randomized manner to make sure that the gender was equally represented in each testing condition. The exact nature of the experiment aim was explained to each fencer. Everybody was paid minimum wage for his or her participation.

5.4.2 Experimental Setup

The Experimental setup was the same that was used in the experiment 1 (Figure 1).

5.4.3 Experimental Design

In the experiment 3, experimental design was the same as experiment 1. That is, the visual feedback of the cursor representing the tip of the index finger was provided (FB). The same with the experiment 1, experiment 3 consisted of three conditions: choice of hand, forced right- and forced left-hand reaching movements to targets positioned across the frontal workspace. Whereas the choice of hand condition tested frequency of selected hand, the forced hand conditions provided equal data sample for both hands to examine movement accuracy, quality and efficiency. Note that we had only one group of fencers (8 participants) for forced right- and left-hand conditions. Half of the group performed the forced conditions with their left arm and the consequent week they were asked to come back and perform the experiment with their right arm. This was opposite for the other half of the group.

5.4.4 Experimental Task

The same experimental task was used like in the experiment 1.

5.4.5 Data Analysis

For the data analysis, we have followed the same procedures that we had done in the experiment 1. Initially, three regions of interest were identified in the frontal workspace in the experiment 3 (Figure 27). In these areas of interest but in the forced hand conditions, six dependent variables that depict sensorimotor performance were quantified across subjects.

The statistical analyses were the same as experiment 1 and 2.

5.5 Results

In this experiment, we aimed to find if long term pattern of practice influences limb selection during a reaching task and underlying mechanism of this behavior. The result of the reaching frequency averaged across all targets and athletes show that right hand usage is substantially higher than that of left hand usage (60% vs. 40%, Figure 28). Note that, however, right hand reaching frequency for athletes decreased 8% when it is compared with non-athletes FB condition (60% for athletes vs. 68% for non-athletes). We rejected our hypothesis which stated higher rate of dominant arm selection for athletes in comparison to non-athletes. An increase of 8% with left non-dominant hand for athletes can be considered as the improved left hand coordination with the result of elite athletic activity, and thus increased non-dominant hand selection. The repeated measures ANOVA showed a significant 2-way interaction (2x32) between hand (L & R) and target (1-32) ($F_{(31,441)}$=165.19, p=.0001). In Figure 27, we show the distribution of reaching frequency between hands across all targets. Similar to the experiment 1 and 2, our approach was to qualify all targets reached significantly more with the left hand to the LF group. The RF group consisted of analogous symmetrical targets to the right side from the MF group, which was formed by targets that showed no significant difference between hands. In the experiment 3, we found only one target with no significant difference between hands (mean difference=10%, p=.99, Tukey HSD) that formed the MF group as outlined in Figure 27. Note that, there 4 targets in the MF region for non-athletes. The LF group included 13 targets that were reached using the left hand with frequency above 70% (p=.001, Tukey HSD). The RF targets were reached using the right hand with the frequency above 80% (p=.0001, Tukey HSD). Similarly to the experiment 1 and 2, we found a significant effect of the distance amplitude on the reaching frequency when considering the shortest and the furthest target in the first parasagittal plane to the left from the midline of the body (p=.0009, Tukey HSD). The right hand usage increased from 15.4±8.01% for the shortest target to 44.5±8.4% for the furthest one. Although not significant (p=.51, Tukey HSD), similar trend was observed in the second parasagittal plane further to the left side, where the right hand usage increased from 3.6±2.7% to 24.5±9.0% respectively. The main finding here is that long term practice led athletes to change their reaching frequency with the left hand being employed on average more frequently in comparison to the non-athletes. The transition area for switching hand selection became much smaller (MF=1 target for athletes vs. MF=4 targets for non-athletes) and was shifted to the right side being now closer to the midline of the body.

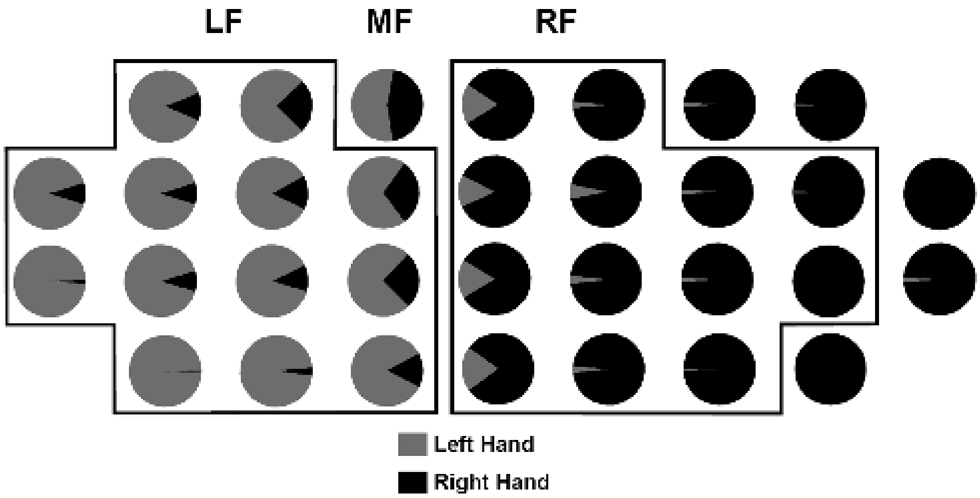

Figure 27. Pie chart of reaching frequency between hands with the distribution of all targets averaged across athletes in experiment 3.

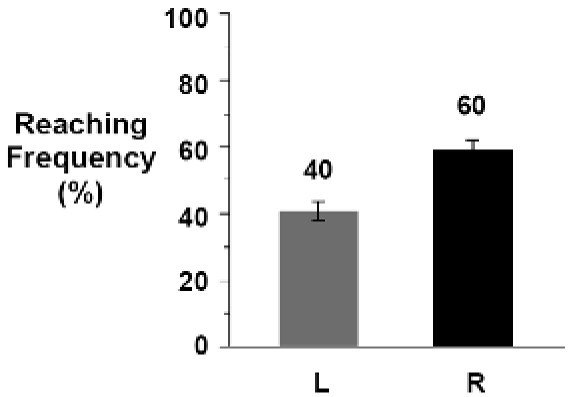

Figure 28. Mean of reaching frequency between hands across all targets and athletes in experiment 3.

In our first and second experiments, movement quality and efficiency explained hand selection behavior and, thus, we concluded that hand preference is an active choice depending on motor performance asymmetries. In our final experiment, in order to explain this hand selection behavior, our three dependent variables that determined accuracy (FPE), quality (HPL) and efficiency (CJW) of the movement were again subjected to repeated measures ANOVA. Similar to the experiment 1 and 2, three more dependent variables were (tangential velocity, acceleration, & deceleration) analyzed to support information about speed of the movements with the directions and increase and decrease in the magnitude of velocity. For this purpose, another group of athletes (see Methods) performed the same reaching task in the FB condition being forced to use either the left or the right hand. Like for the experiment 1 and 2, the dependent measures were collapsed across our three groups of targets (LF, MF & RF) identified based on the reaching frequency.

In Figure 29, we show the distribution of the FPE that defines movement accuracy. The FPE was found to be similar across targets and hands and ranged between 0.011±0.001 and 0.021±0.002. Even though there is a trend for each hand to perform the reaching movements with the better accuracy in its own hemispace, this trend does not look like to make a substantial difference between hands, like 1 or 2mm differences as shown in Figure 30. Thus, it can be said that both hands FPE performance looks similar. This similar performance for both hands also had been found for non-athletes (FB condition). The results of repeated measures ANOVA for athletes did not show a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}$=2.51, p=.09). Furthermore, neither hand ($F_{(1,412)}$=0.08, p=.76) nor target regions ($F_{(2,412)}$=1.05, p=.25) main effect was found to be significantly different. The result of the statistical analysis for athletes is the same as non-athletes. As the statistical analysis did not show a significant interaction for the FPE, this variable cannot explain the hand preference behavior in the choice of hand condition. The FPE for athletes and non-athletes looks very similar for both groups. This means that both groups performed the reaching task with the same accuracy. However, it is worth nothing that athletes' velocity profiles for both hands were substantially faster than non-athletes (velocity results presented later for athletes). Therefore, athletes can perform the reaching task with the faster velocity and similar accuracy compared to non-athletes.

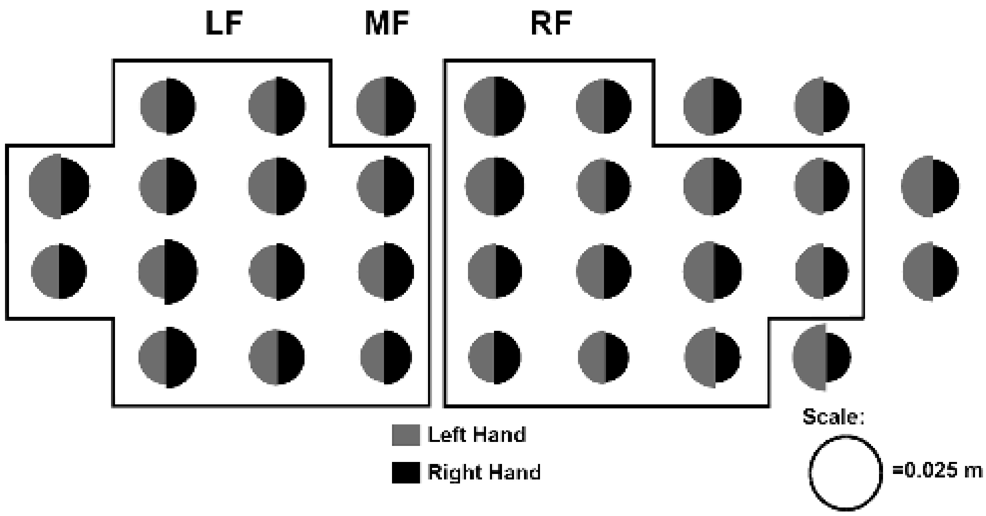

Figure 29. Mushroom plot of FPE between hands with the distribution of all targets averaged across athletes in experiment 3.

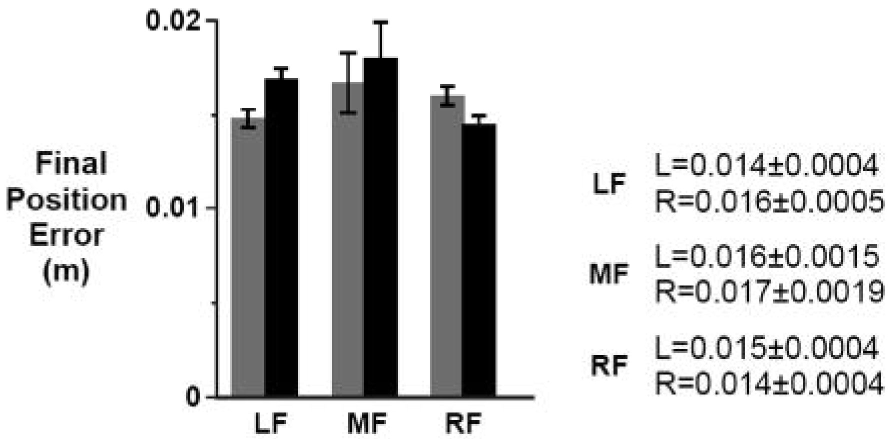

Figure 30. The mean of FPE values across targets regions in experiment 3.

In Figure 31, we show the averaged results of the HPL measure for all targets. Similarly to the non-athletes, athletes performed the most curved movements to the shortest targets in the center region and the least curved movements to the ipsilateral side. However, athletes overall performed reaching movements substantially less curved than that of non-athletes (Figure 32 vs. Figure 8, respectively). In general, the HPL for athletes ranged from 0.03 to 0.07 and right hand movements' curvatures did not change over the target regions, whereas left hand movements' curvatures changed being more curved to the RF region. In addition, there was a trend for right hand to have less HPL across all target regions. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}$=3.45, p=.03). Figure 32 shows the average HPL across subjects and regions of interest. The post-hoc analysis revealed a significant difference only in the RF region where right hand movements were significantly less curved than left hand movements (0.048±0.001 vs. 0.060±0.001, p=.0001, respectively). Although right hand HPL was smaller in the MF and LF regions, this was not found to be significantly different. As there was only one target in the MF region, this may explain the non-significant hand difference in this region. Overall, the result of the HPL reflects the pattern of hand selection behavior in the RF and MF region, which was also the case for non-athletes. In addition, both hands movements were substantially less curved for athletes than for non-athletes. We need to also point out that athletes performed these less curved movements with the substantially faster velocity than non-athletes.

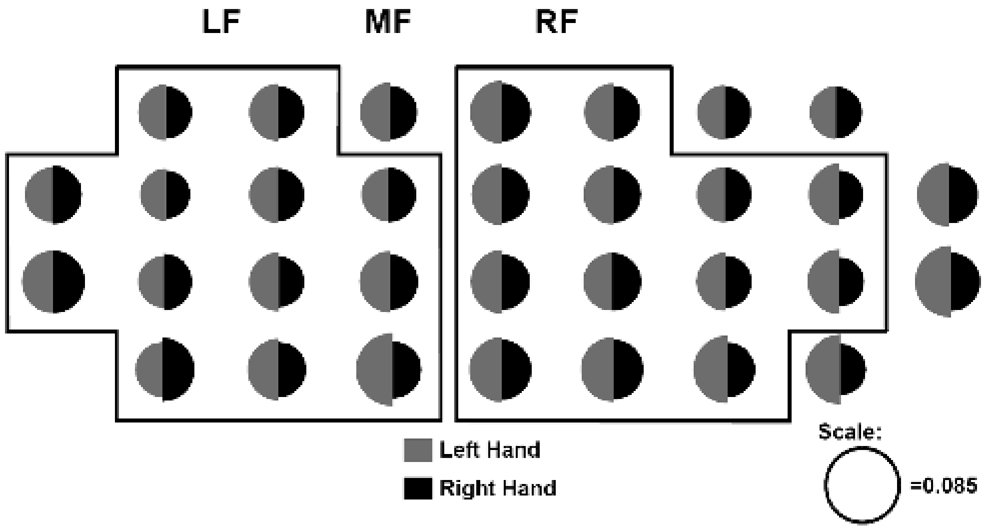

Figure 31. Mushroom plot of HPL between hands with the distribution of all targets averaged across subjects in experiment 3.

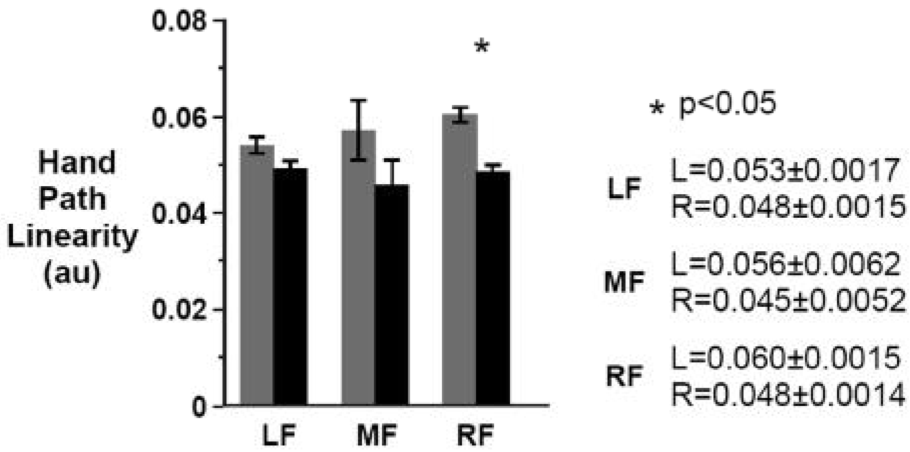

Figure 32. The mean of HPL values across targets regions in experiment 3, $p<0.05$.

The tangential velocity profile of left and right hand reaches in three target regions for athletes was shown in Figure 33. Since we had a requirement for the completion of trials, the peak tangential velocity for both hands was faster when reaching to contralateral hemispace. The same trend had been also observed for non-athletes. We can see in Figure 33 that left hand reaches are faster than right hand reaches in the RF region but slower in the MF and LF regions. On the contrary, right hand reaches are substantially faster in the MF and LF regions but the differences between hands are much higher in the LF region compared to RF region. Statistical analysis showed the similar results. The repeated measures ANOVA displayed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,412)}=114.45$, $p=.0001$) for the velocity. Left hand reaches were significantly faster than right hand reaches in the RF region (0.82 m/s vs. 0.74 m/s, $p=.001$, Tukey HSD). In the MF region, right hand reaches were significantly faster than left hand reaches (1.08 m/s vs. 0.87 m/s, $p=.04$, Tukey HSD). Similar to the MF region, right hand showed significantly faster reaches than left hand reaches (1.03 m/s vs. 0.68 m/s, $p=.0001$, Tukey HSD). Overall, each hand moved faster to the contralateral hemispace to accomplish the task in a given time which was also the case for non-athletes. However, athletes' reaching movements with both hands are considerably faster than non-athletes in all target regions (Figure 33 vs. Figure 10). It has been previously reported that fencers were faster than non-fencers in movements of the upper limbs (Roi & Bianchedi, 2008), thus, our finding on reaching movement velocity is in agreement with that previous study result.

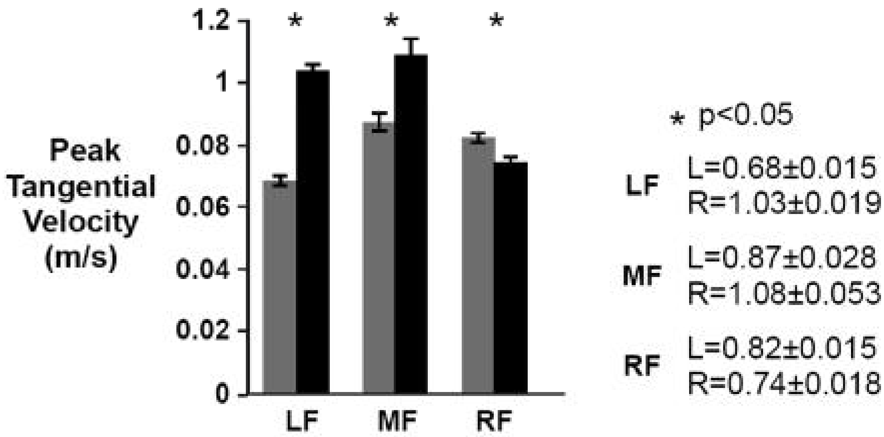

Figure 33. The mean of peak tangential velocity across target regions in experiment 3, $p<0.05$.

The peak tangential acceleration profiles of left and right hand reaches in three regions were displayed in Figure 34. The peak tangential acceleration profiles for athletes showed similar trend as was observed for non-athletes. However, the peak acceleration amplitude of athletes for both hands is much higher compared to non-athletes (Figure 34 vs. Figure 11). This was also the case for the velocity profile. In particular, whereas higher acceleration for right hand is apparent in the both MF and LF regions (Figure 33), similar acceleration for both hands can be seen in the RF region for athletes. Statistical analysis of repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF, & RF) ($F_{(2,464)}=53.93$, $p<.0001$) for acceleration. Post-hoc analysis revealed that acceleration is significantly higher for right hand than for left hand in the MF region (7.09 m/s^2 vs. 5.41 m/s^2, $p=.005$, Tukey HSD) and in the LF region (6.75 m/s^2 vs. 4.80 m/s^2, $p=.0001$, Tukey HSD). However, there was no significant difference in the RF region (left hand: 5.14 m/s^2 and right hand: 5.20 m/s^2, $p=.99$). Similar to the non-athletes, left and right hands accelerations of athletes were the same in the RF region in spite of the faster reaches with left hand to that region. Moreover, right hand acceleration of athletes was found to be faster in MF and LF regions, which was consistent with the velocity profile and this was also the case for non-athletes. In other words, both athletes and non-athletes use the same strategy to accelerate the hand during reaching movements in spite of the fact that athletes' acceleration amplitude is much higher than non-athletes'.

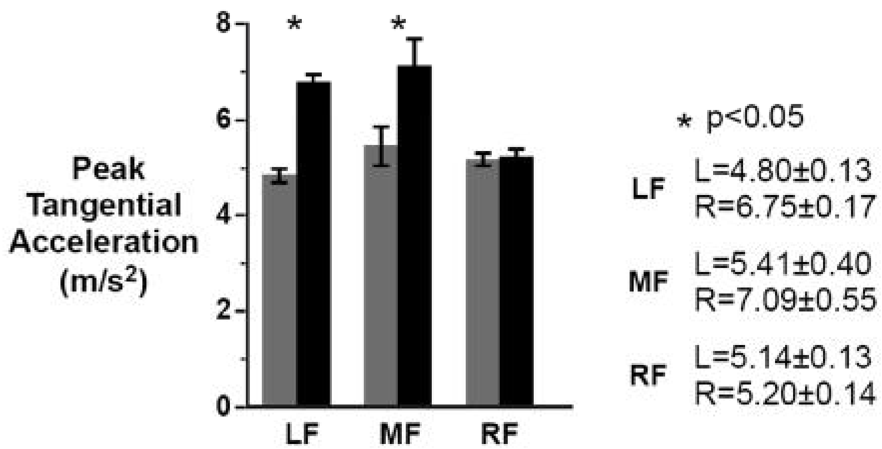

Figure 34. The mean of peak tangential acceleration across target regions in experiment 3.

The deceleration profile of both hands in three regions for athletes was shown in Figure 35. In this figure, it is very clear that right hand deceleration is higher than left hand regardless of target regions. In fact, this pattern was not observed for the non-athletes where there were similar deceleration profiles for both hands in all target regions (Figure 35 vs. Figure 12). The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hands (L & R) and target regions (LF, MF, & RF) ($F_{(2,464)}$=7.08, p=.0009) for deceleration profiles of athletes. Post-hoc analysis revealed that deceleration is significantly higher for right hand than for left hand in LF region (5.98 m/s^2 vs. 4.53 m/s^2, p=.0001, Tukey HSD), in MF region (6.75 m/s^2 vs. 4.99 m/s^2, p=.0001, Tukey HSD), and in RF region (5.36 m/s^2 vs. 4.41 m/s^2, p=.0001, Tukey HSD). Higher velocity and acceleration for athletes in MF and LF regions was followed with higher deceleration in those regions which was not observed in non-athletes. In addition, right hand deceleration was also found to be higher than left hand deceleration in RF region even though left hand reached higher velocity in this region. This pattern was also not observed in non-athletes.

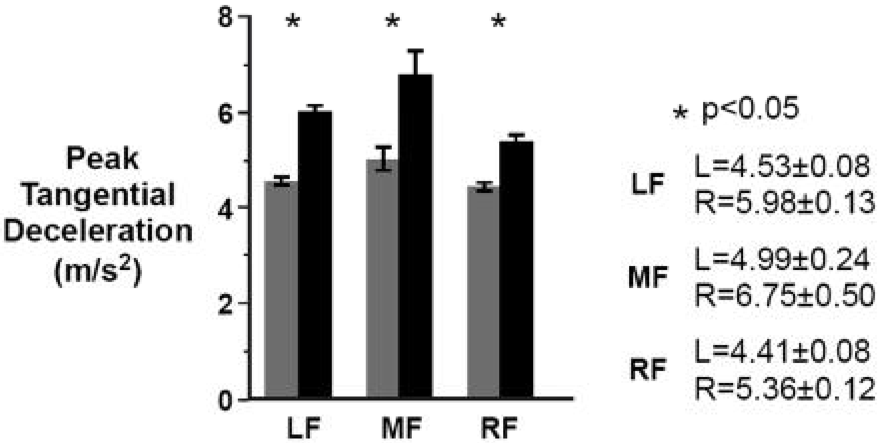

Figure 35. The mean of peak tangential deceleration across target regions in experiment 3, p<0.05.

In Figure 36, we show the distribution of the CJW across the workspace for both left and right hand. As expected and similarly to non-athletes, the least amount of estimated muscle work was spent when reaching to targets closer to the body and the largest amount of work was spent for the furthest movements into contralateral hemispace. The repeated measures ANOVA showed a significant 2-way interaction (2x3) between hand (L & R) and target regions (LF, MF & RF) ($F(2,464)=351.70$, $p=.0001$). In Figure 28B, the left hand showed a significant advantage when reaching to the LF region (1.22 ± 0.05 vs. 4.96 ± 0.19 Nm·rad/s2, $p=.0001$, Tukey HSD) and MF region (2.40 ± 0.23 vs. 4.02 ± 0.50 Nm·rad/s2, $p=.04$, Tukey HSD). This was opposite in the RF region, where the right hand had a significant advantage (1.59 ± 0.08 vs. 3.71 ± 0.17 Nm·rad/s2, $p=.0001$, Tukey HSD). The result of the CJW for athletes displays similar pattern like non-athletes where there was a significant left hand advantage in LF and MF regions and disadvantage in RF region (Figure 14). However, the amplitude of CJW for athletes is higher for both hands than that of non-athletes (Figure 37 vs. Figure 14). Similar to the result of the CJW for non-athletes, the result of the CJW for athletes reflect the hand selection behavior especially in LF and RF regions.

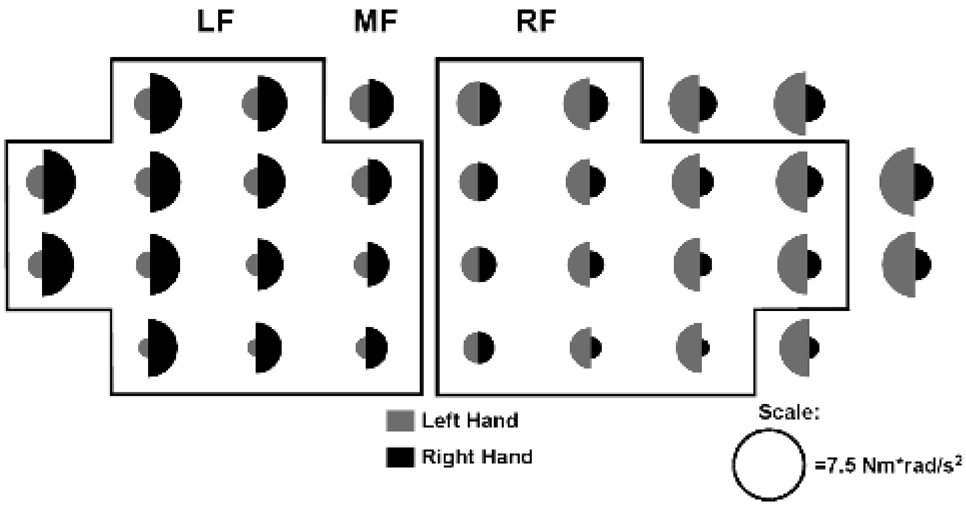

Figure 36. Mushroom plot of CJW between hands with the distribution of all targets averaged across athletes in experiment 3.

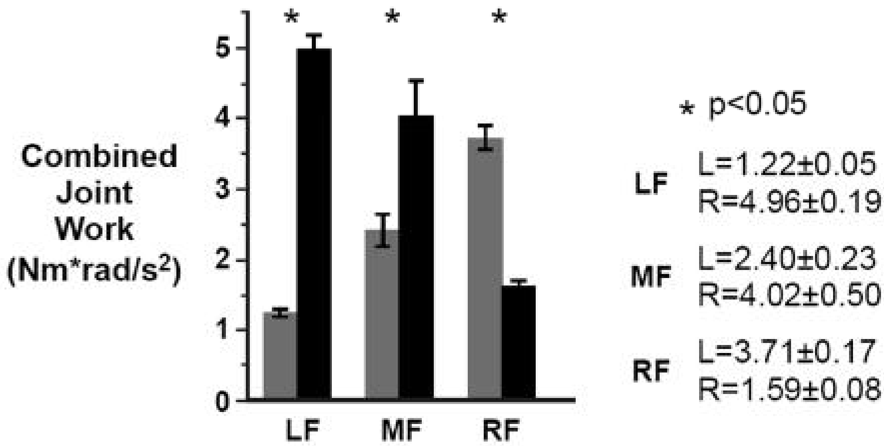

Figure 37. The mean of CJW values across targets regions in experiment 3, $p<0.05$.

5.6 Discussion

In experiment 3, we aimed to explore whether long term practice with predominantly by dominant hand influences limb selection. For this purpose, we asked right-handed fencers to reach targets located in the frontal working space with their either hand. In our first experiment, we found that non-athletes' frequency of hand usage in the working space was detected as 68% for right and 32% for left hand. In our final experiment, we tried to find if the long term practice influences this frequency of hand usage. Similarly to the experiment 1 and 2, we tried to find the effect of distance amplitude on this reaching frequency. We also aimed to find the underlying mechanism that can explain the pattern of hand selection among athletes and make a comparison with non-athletes.

Similarly to the first and second experiments and to the previous studies (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003), the result of the choice of hand condition across all targets for athletes also showed more significant reaches with right hand than with left hand (60% vs. 40%, respectively). However, the percentage of left hand reaches increased 8% from non-athletes to athletes. In other words, athletes tend to prefer their left hand more than non-athletes do (40% vs. 32%, respectively). The more left hand usage for athletes resulted with change of the transition area for switching hand selection when compared to non-athletes. This transition area consisted of only one target in experiment 3 and was shifted to the right side being closer to the midline of the body. In fact, the finding of reaching frequency for athletes is very similar to non-athletes finding with no visual feedback condition (NFB). In experiment 2, we had tested non-athletes under the NFB condition and found more left hand usage compared to available visual feedback (FB) condition (40% vs. 32%, respectively). This is also what we found for athletes under the FB condition. Thus, the main finding in experiment 3 for athletes is that the distribution of reaching frequency was changed with the more frequently usage of left hand in comparison to non-athletes FB condition. In fact in a study with judo wrestlers, Mikheev et al. (2002) also reported that athletes preferred more frequently to perform certain movements with the left hand than non-athletes, although they were overall right-handed. In experiment 3, our finding in the choice of hand condition appears similar with those of Mikheev et al. (2002). Furthermore, previous research has also reported that unimanual practice requiring sequential finger movements of the non-dominant left hand induced a persistent shift of hand preference for this task being preferred more frequently by left hand (Teixeira & Teixeira, 2007; Teixeira & Okazaki, 2007). Even though fencers predominantly practice with their right dominant hand, they also use their non-dominant left hand to be on the balance during the on-guarde position and the attack (Roi & Bianchedi, 2008). It has been also previously stated that practicing an activity with one arm can affect subsequent performance of the other arm (Latash, 1999; Morton, Lang, & Bastian, 2001; Sainburg & Wang, 2002; Wang & Sainburg, 2004). Even though short-term effect of interlimb transfer of training in the above studies was observed, this interlimb transfer may occur during the long-term fencing training and non-dominant arm may increase its proficiency during the right arm training. In our second experiment, we found that left hand has better motor performance during the occlusion of visual feedback. It is also worth to think that fencers may rely less in visual feedback during their practice regime as they do not focus on their weapons and just focus on their opponent reactions. Thus, this may also lead to have more frequent reaches with the left non-dominant arm as it has more proficient movement with the proprioception sensory information. To sum up, the result of choice of hand condition in experiment 3 showed that elite athletic activity might improve non-dominant arm coordination, and thus resulted with increased non-dominant arm selection.

In accordance with experiment 1 and 2, we found a significant effect of the distance amplitude on the reaching frequency when considering the shortest and the furthest target in the first parasagittal plane to the left from the midline of the body. Similar trend was also observed in the second parasagittal plane further to the left side but it did not reach the significant level. Thus, the usage of right hand increases when the target is located further to the body. Reaching to the furthest targets require more shoulder and elbow excursions, which may raise the difficulty to coordinate intersegmental dynamics. As we know from previous studies, right hand has an advantage in coordinating intersegmental dynamics during reaching (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002; Shabbott & Sainburg, 2008), this may lead people to reach farther targets with their right dominant hand.

In order to explain hand selection behavior for athletes in experiment 3, we had also forced conditions where we asked participants to reach with either left or right hand. The data from the forced conditions gave us information if the change in the hand section behavior was caused by the change in the interlimb difference. We had six dependent variables and we made comparisons considering three regions of interest and hands.

The result of movement accuracy (FPE) across target regions (LF, MF, & RF) between hands did not show a significant interaction for athletes. Moreover, there was neither target regions nor hands main effect. That is, there is no advantage in FPE across both hands and target regions. This was also the case in non-athletes FB condition. Moreover, peak tangential velocity did not result in an accuracy difference on target regions. The peak tangential velocity was higher in the LF region for right hand than for left hand and vice versa in the RF region. However, this did not make any interlimb difference between hands in terms of FPE across these target regions. In addition, the result of FPE for athletes and non-athletes looks very similar for both groups (L=0.014 –

R=0.016 vs. L=0.015 – R=0.012 in LF region, L=0.016 – R=0.017 vs. L=0.014 – R=0.013 in MF region &, L=0.015 – R=0.014 vs. L=0.015 – R=0.013 in RF region, respectively). That is, both groups performed the reaching task with the same accuracy. However, it is worth noting that athletes' velocity profiles for both hands were substantially faster than non-athletes. Thus, although both athletes and non-athletes performed the reaching movements with the similar accuracy, athletes' reaches were considerably faster compared to non-athletes reaches. Note that, both groups were given the same instruction to perform the task by the experimenter. In a study comparing ballet dancers and non-dancers in a position-matching task, it has been stated that the accuracy in position-matching in the upper limb was found to be greater for ballet dancers (Riddoch & Ramsay, 2001). Similarly, in a matching task, modern dancers had smaller errors compared to non-dancers and Irish dancers. However, no differences in matching accuracy were seen between Irish dancers and non-dancers, although Irish dancers moved faster than non-dancers. Authors concluded that faster movements even with lower limbs could explain to have faster upper limb movements for Irish dancers (Schweiger & Brown, 2010**)**. The observed lack of enhanced accuracy for athletes in our experiment may be related to task employed to test movement accuracy. In the above studies, researchers used position matching task which mainly depends on proprioceptive limb acuity. In our task, we used a reaching task with available visual information. Therefore, available sensory information during the movement execution might differently affect the accuracy of the movement. Overall, as there was no significant interlimb difference across target regions in terms of FPE, this variable cannot explain results of the reaching frequency in the choice of hand condition for athletes like it was found for non-athletes.

Analysis of the hand path linearity (HPL) data which represents the quality of movement revealed a significant interacti on between hands and target regions. Straighter right hand movements were observed especially in RF region. Although right hand movements were less curved in MF and LF regions, this was not found to be significantly different. The observed lack of significance in MF region is because of having one target and high standard errors for both hands in that region. Whereas left hand showed less curvature hand path linearity in LF region, right hand path linearity stayed the same in all regions. The deficiency in torque strategies for left hand when reaching to right hemisphere (Bagesterio & Sainburg, 2002) could result with more curvature movements in RF region. When it is compared to non-athletes, athletes' HPL, in general, was found to be less curved, although performed with faster movements. In their study, Williams and Walmsley (2000) introduced recordings of EMG activity during measurement of response times between elite fencers and novice subjects. They have found that elite fencers displayed more coherent muscle synergies and more consistent pattern of muscle coordination than novice subjects. Thus, more coherent muscle synergies for fencers may lead to have less curved movements than non-athletes. In accordance with the result of choice of hand condition, the result of the HPL for athletes reflects hand selection behavior especially for RF and MF regions.

In order to provide information about the speed of the reaching movements with the directions and increase and decrease in the magnitude of velocity, we calculated peak tangential velocity, acceleration, and deceleration across target regions between hands. Similar to non-athletes, peak tangential velocity varied with movement distance for both hands for athletes. However, athletes' velocity profiles for both hands are substantially faster than non-athletes. It has been previously found that fencers were faster than non-fencers in movements of the upper limbs (Roi & Bianchedi, 2008), thus, our finding on reaching movement velocity is in agreement with that previous study result. The reason to have faster movements for athletes may be related to their long term practice regime. In addition, as they mainly practice fast pointing movements in their exercise settings, this can lead them to have faster movements than non-athletes. Note that, even though fencers predominantly practice with their right dominant hand, both left and right hands' velocities for fencers are faster than non-athletes. This could support the idea of interlimb transfer during the long-term fencing training. Acceleration profile of left and right hand for athletes was the same as non-athletes. Whereas right hand peak acceleration was higher than left hand in LF region, left hand peak acceleration was found to be similar to that of right hand in RF region. Thus, similar to non-athletes, peak velocity and acceleration of right hand reaches for athletes varied across target distances and can be viewed as a good predictor for movement distances which was also found in previous studies (Brown & Cooke, 1986; Ghez & Gordon, 1987; Krakauer, Gordon, Veytsman, & Ghez, 2002; Sainburg & Schaefer, 2004). However, only peak velocity of left hand varied across target distances but not acceleration. Therefore, our conclusion in the experiment 1 and 2 is also valid in the experiment 3. This result shows that long term practice predominantly with dominant hand does not change the mechanism responsible for the specifying movement distance. However, the amplitude of peak tangential acceleration for athletes is considerably higher than non-athletes. The similar finding was also observed for peak tangential deceleration. In addition, right hand deceleration was found to be higher in all target regions than left hand deceleration. This strategy used by athletes is very different compared to non-athletes where both hands decelerations were the same in all target regions. This might be also related to the fast pointing movement practice with right hand during long term training regime.

Similar to non-athletes, the analysis of the modulation of the movement efficiency defined by the CJW displayed a significant difference between hands on the RF region for athletes. Less amount of estimated muscle work was spent when reaching to targets located on the RF region by right hand. On the MF and LF regions, that was in favor of left hand. That is, left hand reaches to the MF and LF reaches were more energetically efficient than right hand reaches. In general, the result of CJW reflects hand selection behavior especially for RF and MF regions.

In summary, we found that right hand reaching frequency is more than that of left hand in the choice of hand condition for athletes. However, athletes used their left hand more than non-athletes. This means that hand preference is affected by an external factor, namely long term training. The data from the forced condition showed no interlimb differences in FPE across target regions but significant interlimb differences in HPL (RF region) and CJW (LF, MF, & RF regions) for athletes. It is also worth nothing that although athletes' reaching movements were substantially faster than non-athletes' reaches, athletes had straighter HPL and similar accuracy compared to non-athletes. In view of underlying mechanisms of hand selection behavior for athletes, as there was no interlimb difference in FPE, this variable cannot explain results of the reaching frequency in the choice of hand condition. However, the results of the HPL together with the CJW corresponded well to the hand selection. Similar to experiment 1 and 2, this suggests that the choice of hand is more likely to be an active decision based on evaluation of quality and energetic efficiency of the movements. Putting together all the results obtained here, we are led to the view that, the interlimb differences in sensorimotor performance associated with handedness dictate the hand selection in our reaching task.

CHAPTER 6

GENERAL CONCLUSION AND RECOMMENDATIONS

6.1 General Conclusion

This dissertation presents three experiments to investigate the general distribution of hand preference across the reachable working space, as well as the effect of sensory information about the reaching hand, and if this distribution is affected by external factors, such as long term practice. In addition, we also investigated the underlying mechanisms of this hand preference behavior with the obtained kinematic data.

Experiment 1 explored the distribution of hand preferences across the workspace among non-athlete right-handed participants, as well as the role that visual feedback might play in this distribution. The results suggested that the choice of hands is related to the mechanical efficiency with which each arm performs a given movement. While each arms reaches almost exclusively to its own lateral workspace, which was also stated in previous studies (Gabbard & Rabb, 2001; Mamolo et. al, 2004; Stins, Kadar, & Costall, 2001), the dominant arm reaches substantially more to the midline regions. In addition, the frequency of dominant arm reaches increases with the distance of the target from the start position, a finding consistent with the idea that the choice is based on dynamic costs (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002; Shabbott & Sainburg, 2008). In order to assess plausible costs associated with these movements, we measured kinematics for each arm to all the reachable targets in the workspace. Comparison of dependent variables that reflected task accuracy, timing, movement linearity, and dynamic efficiency showed that the latter two variables best explained subjects' choices. Thus, even though movements in the midline required symmetric positions for both arms, dominant arm coordination was more efficient, resulting in lower dynamic cost for dominant, as compared with non dominant arm movements. In addition, the result of the kinematic data also showed that the mechanisms responsible for the different movement extents were quite distinct for each arm, which is in agreement with the previous data (Brown & Cooke, 1986; Ghez & Gordon, 1987; Krakauer, Gordon, Veytsman, & Ghez, 2002; Sainburg & Schaefer, 2004). Whereas peak tangential velocity and acceleration varied across target distances for dominant hand, only peak tangential velocity varied across target distances for non-dominant hand.

Based on the findings described above, we hypothesized that the choice of hand for a given target is based on the proficiency on the energetic cost and dynamic efficiency associated with the movement. If the cost is lower and dynamic efficiency is better for the left arm, the left arm will be chosen, and vice versa. Alternatively, subjects' might have become habitual over a lifetime of use. In experiment 2, we tested our hypothesis by presenting a condition that we knew would decrease the dynamic efficiency of dominant arm movements. Previous research has demonstrated that movements made without visual feedback are less efficiently coordinated than those made with visual feedback (Bagesterio & Sainburg, 2002; Goble, Hurvitz, & Brown, 2006; Goble & Brown, 2007; Lenhard & Hoffmann, 2007; Wang & Sainburg, 2006). We, thus, predicted that removing visual feedback will 1) decrease the efficiency of right arm movements, compared to that of left arm movements, and 2) increase the frequency of left arm choices for targets in the subjects' mid-region of the workspace. The result of the choice of hand condition by removing visual feedback indicated more left hand usage compared to available visual feedback about the moving hand. Thus, transition area switching from dominant to non-dominant hand shifted to the right side being closer to the midline of the body. Similar to experiment 1, we found a significant effect of the distance amplitude on the reaching frequency in experiment 2. Thus, occlusion of visual feedback did not affect the distribution of distance amplitude on the reaching frequency. Kinematic data displayed a superior performance in terms of final position accuracy in favor of left hand regardless of the target regions, which was also found in previous studies (Bagesteiro & Sainburg, 2002; Goble & Brown, 2008; Guiard, Diaz, & Beaubaton, 1983; Lenhard & Hoffmann, 2007; Sainburg, 2002; Sainburg & Wang, 2002). As the quality and energetic efficiency of the left hand movements enhanced in the left hemispace, the frequency of left hand usage also increased accordingly. Thus, the choice of hand is more likely to be an active decision based on evaluation of quality and energetic efficiency of the movements rather than a life time habit.

Our final experiment examined the hypothesis that long term patterns of practice should influence limb selection choices. Some researchers suggested that motor preferences as well as the cortical representations of body are not predetermined entities, but can be adaptable through experience, for instance sport or musical practice (Elbert et al., 1995; Mikheev et al., 2002). Thus, we hypothesize that elite athletic performance should alter movement proficiencies with both hands. This hypothesis predicts that the pattern of hand selection in elite athletes should be different, as a group, than that of non-athletes. We hypothesized that extensive practice with the dominant arm should increase dominant arm selection in comparison to non-athletes. To test this hypothesis, we compared limb selection patterns in elite fencers and non-athletes. Fencing was chosen as an activity that challenges upper limb coordination, quite extensively and focuses predominant, although not exclusively on dominant arm performance. We rejected our hypothesis which stated higher rate of right hand reaches on athletes in comparison to non-athletes. Our results showed that our athletes increased the frequency of non-dominant arm reaches, shifting the line of symmetry for left and right arm reaches toward midline. The quality of this difference was an increase in non-dominant arm selection, and a corresponding improvement, relative to non-athletes, in non-dominant arm coordination. We confirmed that, the pattern of hand preference was different between elite athletes and non-athletes. We conclude that elite athletic performance has a substantial effect on improving performance and use of the non-dominant arm. We have also found that although both athletes and non-athletes had very similar performance in movement accuracy, athletes' movements, as a group, were considerably faster and straighter compared to non-athletes. This could be explained by the effect of long term practice.

In summary, we conducted 3 different experiments to examine the factors that influence arm selection for reaching tasks in humans. First of all, we characterized the distribution of arm choices across a large horizontal workspace, and showed that the choice of arms is related to the energetic cost and dynamic efficiency of the movements. Secondly, we showed that the choice of hands changes under different visual feedback conditions, demonstrating that the choice is active and not habitual. Finally, we showed that elite athletes have different patterns of limb selection than non athletes. Specifically athletes show improved coordination in their non-dominant arms, which apparently increases the selection of this arm for reaching.

6.2 Recommendations

Current literature on hand preference mainly focuses on the qualitative data to explain this phenomenon. Our detail analysis with the quantitative data indicated that hand selection process is associated with sensorimotor performance asymmetries and affected by long term practice. Therefore, right-handers' preference for selecting right arm to reach to the contralateral hemisphere next to the body midline is an active choice, not a life-time habit. In the future studies, it is also important to investigate if there are some other factors that may influence this active choice, like decreasing time for decision making.

All the data for kinematic and kinetic analyses were collected in two-dimensional space. In the future studies, it is also recommended to apply three-dimensional space for the kinematic and kinetic analyses so as to get more detailed analysis.

One of the main findings of this dissertation is that hand preference is an active choice based on quality and energetic efficiency of the movement. It is very crucial to find when people consciously start to make this active decision. Although there are some studies in which researchers investigated hand selection pattern among children, no study indicated developmental effect of this conscious decision on hand preference. Thus, it is important to examine hand preference phenomenon considering the developmental perspective. In addition, there is also lack of knowledge on elderly people's hand selection pattern. Recently, Przybyla and his colleagues (2011) found motor asymmetry reduction on older adults. Thus, it is also very essential to investigate whether reduced asymmetry in older adults can cause a different pattern of hand selection behavior.

In this dissertation, we have found an effect of long term fencing practice on hand preference. In Fencing, fencers predominantly use their dominant hand but they also use their non-dominant hand to keep their balance. However, it is also worth to investigate whether the effect of long term practice will be different in some other types of sports requiring more symmetrical upper arm movements.

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APPENDICES

A. INFORMED CONSENT FORM AND ETHIC COMMITY APPROVAL

PENNSTATE

Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of project: Interlimb Differences in Motor Control and Learning

Person in charge: Robert L. Sainburg, Ph.D.
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University Park, PA 16802
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I. This section provides an explanation of the study in which you are being asked to participate:

A. Purpose of the Study: The purpose of this research is to define mechanisms that underlie handedness (use of right or left hand) and propose that the non-dominant arm does have advantages over the dominant arm for some specific tasks like holding a loaf of bread while it is being sliced. We are also examining whether such behavioral asymmetries change as a function of age. Additionally, we would like to know whether there are differences between the arms' performances when they are moved together in a common task, like carrying a tray, as compared to when they are moved individually during one-handed tasks, like hand-writing or throwing. These questions will be addressed by examining recordings of arm movements and muscle activity as people interact with a computer game in our laboratory.

B. Procedures: Measurements of the lengths of your forearm and upper arm will be taken with a measuring tape, and you will be weighed using a bathroom style scale. You will then sit at a table, with your arm supported on an air-sled system. This supports the arm on the table surface, while eliminating friction between the arm and the tabletop. The effect is that the arm freely glides over the table surface. Your arm will be fitted to a brace, which is designed to restrict motion of your wrist and fingers, and strapped to this air-sled with Velcro straps. This should not be uncomfortable, but you may remove your arm from the support at any time, if it becomes uncomfortable.

A computer game will be projected on a screen positioned above your arm. Though you will not be able to see your hand, you will see the position of your hand as a cursor, projected on the screen. You will be asked to position this cursor in a start-circle in the middle of the screen. You will be asked to move your hand toward targets presented on the screen. Points will be awarded for accuracy. You may be asked to move your dominant arm, your non-dominant arm, or both arms at the same time. In some cases, the experiment may seem more difficult than you would expect. This is because the experimenter may change the position of the cursor relative to your hand, or may disrupt your movement. Movement disruptions may occur using an external mass (~1 kg or 2.2 pounds), or using a robotic device. (This robotic device has been widely used for rehabilitation purposes, has several built-in safety features, and has been regularly checked for safety purposes). How you adapt to these conditions is part of the information being studied.

A magnetic movement sensor, attached to a wire, will be strapped to your upper arm, while another sensor will be attached to the air sled device. The sensor is light and safe and is the same device used in many video games in arcades to sense the movement of a joystick. The position of the sensor will be recorded during your movements, to provide a record of how your elbow and shoulder angles change.

We may record muscle activity, using electrodes (sticky patches). These recordings are similar to having your heart recorded with an electrocardiogram (EKG). These recordings are called electromyograms (EMG). Small metal contacts will be taped over your muscles, using medical tape. As your muscles are used, they generate small electrical signals that are recorded by these electrodes and stored on a computer. These electrodes can generate no electricity and so is no risk of electrical shock.

C. Risks and Discomforts: This study involves minimal risk; that is, no risks to your physical or mental health beyond those encountered in the normal course of everyday life. In participating in this research, you may experience some minor discomfort associated with remaining seated for a 2-hour session with your arm constrained to a brace. However, at any time, you can request a break to stretch, move about the room, visit the lavatory, and remove the arm brace.

D. a. <u>Benefits to Participant:</u> There is no benefit to the participant, other than the opportunity to participate in research that may lead to improved treatments for patients with stroke, Parkinson's disease and Cerebral Palsy.

b. <u>Benefits to Society:</u> This research will provide information about how the control of movement is organized in the brain and how this organization contributes to handedness. Such information is important for improving rehabilitative training for patients with stroke, Parkinson's disease, and Cerebral Palsy. Such information can also contribute to better training strategies for athletes, who often must overcome natural deficits in using the non-dominant limbs.

E. <u>Duration</u>: Your participation in this research will take approximately 4 hours, separated into two sessions held from 1 to 7 days apart. A research assistant will contact you to schedule the second session.

F. <u>Statement of Confidentiality</u>: Your participation in this research is <u>confidential</u>. This study does not involve use of audio or video tape recordings. Any personal information that you supply will remain confidential. In the event of publication of this research, no identifying information will be disclosed. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Dept. of Health and Human Services; The Penn State University Institutional Review Board (IRB); and The Penn State University Office for Research Protections.

G. <u>Right to Ask Questions:</u> Please contact Dr. Robert Sainburg at 814-865-7938 with questions, complaints, or concerns about the research. You can also call this number if you feel this study has harmed you. If you have questions, concerns, or problems about your rights as a research participant or would like to offer input, please contact Penn State's Office for Research Protections (ORP) at (814) 865-1775. The ORP cannot answer questions about research procedures. Questions about research procedures can be answered by the research team.

H. <u>Injury Clause:</u> Medical care is available in the event of injury resulting from research but neither financial compensation nor free medical treatment is provided. You are not waiving any rights that you may have against the University for injury resulting from negligence of the University or investigators.

I. <u>Compensation:</u> In return for your participation, you will be given $7.50 per hour as compensation. If at any time you discontinue participation in the study, you will be compensated for the time that you did participate.

J. <u>Voluntary Participation:</u> Your participation is voluntary. You are free to stop participating in the research at any time, or to decline to answer any specific questions, or participate in procedures without penalty. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

You must be 18 years of age or older to consent to participate in this research study. If you consent to participate in this research study and to the terms above, please sign and date this document.

You will receive a copy of this document to maintain for your files.

______________________________ ______________

Participant's Signature Date

______________________________ ______________

Person Obtaining Consent's Signature Date

B. DATA COLLECTION SHEET

Name

Address

Phone #

Height

Weight

Start Time

End Time

Total Time

Amount Paid

Signature of Subject

Signature of Investigator

C. HANDEDNESS QUESTIONNAIRE

Handedness Questionnaire: This is a questionnaire to determine which side you use for manual activities. In the following questions, mark the letter (R) if you perform the certain activity with the right hand; (L) if you perform it with the left hand; and (E) if you can perform it easily with either hand. In all of these activities, consider your hands empty when you begin to perform them.

	R	L	E
1. Which hand turns the knob in opening a door?			
2. Which hand throws a ball?			
3. With which hand do you usually hold a glass or cup, when drinking?			
4. Which hand holds a hammer while hammering?			
5. Which hand holds the top when opening a jar?			
6. Which hand holds the scissors while cutting?			
7. Which hand pushes the light switch on the wall?			
8. Which hand distributes cards when dealing them?			
9. Which hand holds the tissue when you blow your nose?			
10. Which hand waves goodbye?			
11. Which hand tosses a coin?			
12. Which hand strikes a match?			
13. Which hand sets a watch?			
14. Which hand holds a toothbrush?			
15. Which hand takes money from a purse/wallet?			
16. Which hand holds the knife when cutting a loaf of bread?			
17. Which hand directs the thread through the eye of a needle?			
18. Which hand holds the spoon when stirring in a bowl?			
19. Which hand holds the comb/brush when you comb/brush your hair?			
20. Which hand turns the pages in a book?			
21. Which hand holds the knife when peeling a potato?			
22. With which hand do you write?			
23. With which hand do you use an eraser on paper?			
24. Which hand cuts with the knife when eating (with fork)?			
25. Which hand uses the saltshaker?			
26. With which hand do you bounce a rubber ball (basketball) on the floor?			
27. Which hand is on top when you applaud?			
28. With which hand do you draw a sketch or picture?			
29. Which hand turns the water faucet when you hold no glass in either hand?			
30. With which hand do you pick up a quarter from the floor?			
31. From which shoulder do you swing a bat?			
32. Which hand uses an eraser on a blackboard?			
33. Which hand is at the upper end of the handle when shovel?			
34. Which hand holds a tennis racquet (badminton/racquetball/squash/tennis table)?			
35. Which hand puts the key in the door keyhole?			

- Do you consider yourself: Right-handed Left-handed Ambidextrous

- Is there any activity not in this list that you do consistently with your dominant hand, if so, please explain.

D. TÜRKÇE ÖZET

SENSORİMOTOR PERFORMANS ASİMETRİSİ VE EL TERCİHİ

Giriş

Dünyadaki genel popülasyona bakıldığında, yaklaşık olarak insanların %90'ının sağ elli oldukları (Caliskan & Dane, 2009; Jung & Jung, 2009; Perelle & Ehrman, 1994; Vuoksimaa, Koskenvuo, Rose & Kaprio, 2009) ve dinamik aktivite gerektiren işlerde sağ ellerini tercih ettikleri görülmektedir. Günlük hayatta yaptığımız birçok aktivite örneğin diş fırçalamak, saç taramak, televizyonun düğmesine basmak gibi, farkında olmadan otomatik olarak yaptığımız aktivitelerdir. Yapılan bu aktivitelerin zorluğuna göre sağ veya sol elimiz tercih ederiz. Ekmek kesme veya domatesin kabuğunu soyma gibi işlerde ise her iki elimizi de kullanırız. Bu tür işlerde genelde baskın olmayan el sabitleme işini, baskın olan el ise dinamik hareket gerektiren işi yapar. İnsanların hangi ellerini kullandıkları genellikle anketler kullanılarak tespit edilmiştir. Ancak sağlak veya solak olma ile bazı durumlarda sağ veya sol elimizi tercih etme aynı anlama gelmemektedir. Eğer yapılacak iş üst düzeyde performans gerektirmiyorsa o zaman kişi baskın olmayan elini de bu işi gerçekleştirmek için kullanabilir. Dolayısıyla hareket yeterliliğinden ziyade başka faktörlerde seçilecek olan el tercihinde önemli olabilir. Bunlarda biri elin uzanılacak cisim veya objeye olan yakınlığı olabilir. Ancak eğer yapılacak iş beceri ve koordinasyon gerektiren bir iş ise, o zaman baskın eli tercih etme olasılığı da artmaktadır.

El tercihi genelde değişmeyen bir biyolojik bir özellik olarak varsayılmasına rağmen, nesneye olan yakınlık veya işin gerektirdiği dikkat kapasitesi de el tercihini etkileyen faktörler olarak bulunmuştur (Gabbard, Tapia, & Helbig, 2003; Gabbard, Rabb, & Gentry, 1998; Gabbard & Helbig, 2004; Gabbard & Rab, 2000; Leconte & Fagard, 2006; Mamolo, Roy, Bryden, & Rohr, 2004). Bu çalışmalarda yapılacak olan iş ve işin içeriği hangi elin seçileceğini etkilemektedir. Örneğin ulaşılacak nesnenin büyük veya küçük olması, ya da boş veya dolu olan bir bardağa uzanma istenildiğinde, kişilerin hangi ellerini tercih edecekleri farklılık göstermektedir.

Bu alan ile ilgili yapılan çalışmalara bakıldığında, uzanma gerektiren hareketlerde genelde kişilerin baskın olan sağ ellerini yaklaşık olarak %60 oranında tercih ettikleri bulunmuştur (Gabbard & Helbig, 2004; Helbig & Gabbard, 2003). Dolayısıyla sağ eli baskın olan kişiler vücutlarının orta noktasında ve vücutlarının orta noktasına yakın olan sol tarafta da sağ ellerini tercih etmektedirler. Bu çalışmaların hepsinde kişilere 7 veya 9 adet hedef veya obje gösterilmiş ve bu hedef veya objelere uzanmaları istenmiştir. Kim ve arkadaşları (2007) yakın zamanda insanların neden sağ ellerini vücudun sol tarafında da kullandıklarını bulmak için kinematik verilere dayanarak bir çalışma yapmışlardır. Kendi çalışmalarında anlamlı bir sonuç bulamamalarına rağmen, sağ elin vücudun sol tarafında da kullanılmasının nedenini, Sainburg ve arkadaşları (2000, 2002) tarafından daha önce ortaya koydukları sağ elin sol ele göre daha etkili bir tork stratejisi olduğu ile açıklamışlardır. Sainburg ve arkadaşları (2000, 2002) sağ elin daha etkili bir tork stratejisine sahip olmasını *Dinamik Dominant Hipotezi* ile adlandırmışlardır. Bu hipotez sağlak olan kişilerde, sağ elin koordinasyon ve dinamik iş gerektiren hareketlerde, sol elin ise sabitleme gerektiren hareketlerde daha etkili olduğunu ortaya koymaktadır (Duff & Sainburg 2002; Sainburg 2002; Wang & Sainburg 2004). Bu hipoteze göre; hız, yöne ve mesafe bakımından eşit olan hareketlerde sağ elin sol ele göre daha az kassal tork uyguladığı vurgulanmaktadır. Dolayısıyla sağ elin hareketleri sol ele göre daha etkili olmaktadır. Başka araştırmacılar da sağ ve sol arasındaki performans farklılıklarının görsel veya proprioseptiv algılamalardan etkileyeceğini söylemişlerdir (Goble & Brown, 2007; Goble & Brown 2008; Goble & Brown, 2010). El ile ilgili görsel bilgi olmadan yapılan eşleştirme hareketlerinde sol elin doğruluğunun sağ ele göre daha iyi olduğu bulunmuştur (Goble & Brown 2008; Lenhard & Hoffman, 2007). Bunun yanında el tercihinin uzun süreli yapılan fiziksel egzersizlerden etkilendiğini ortaya koyan çalışmalarda bulunmaktadır (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Mikheev ve ark., 2002).

Sonuç olarak bu doktora tezi kapsamında insanların el tercihini etkileyen faktörlerin neler olabileceği araştırmak için üç farklı deney yapılmıştır. Görsel veya proprioseptiv bilginin sağ ve sol el arasındaki performansa olan etkisi farklı olduğu için ilk ve ikinci deneyde sırasıyla bu duyuların el tercihini nasıl etkileri araştırılmıştır. Son olarak uzun süreli yapılan fiziksel egzersizin el tercihi ve sağ ve sol arasındaki performans farklılıklarına olan etkileri araştırılmıştır.

Materyal ve Metod

Bu çalışmada toplam üç deney yapılmıştır. Birinci ve ikinci deneye 48 sporcu olmayan kişi katılmıştır. Uzunu süreli yapılan fiziksel antrenmanın el tercihine olan etkisini araştırmak için de eskrim sporu yapan toplam 10 kişi üçüncü deneye katılmışlardır. Bütün katılımcılar sağ ellerini baskın olarak kullanan kişilerden seçilmişlerdir. Kişilerin hangi ellerini baskın olarak kullandıklarını belirlemek için Edinburgh El Tercihi anketi kullanılmıştır. Deneyin genel amacı ve deneyle ilgili açıklamalar katılımcılara sözel olarak anlatılmıştır. Deneylerin hepsi Amerika'da bulunan Penn State Üniversitesinde yapılmıştır. Deneylerle ilgili etik kurulu onayı bu üniversiteden alınmıştır.

Bu tez'de kullanılan deney düzeneği şekil 1'de gösterilmiştir. Şekildeki gibi katılımcılar yüksekliği ayarlanabilir bir sandalyeye oturup, üst kollarını masanın üstünde yer alan kızak gibi bir yapıya koymuşlardır. Bu yapının altında yer alan mekanizmadan kompresör aracılığı ile hava verilmiş, dolayısıyla katılımcıların kollarını sürtünme ve yerçekimi olmayan bir ortamda hareket ettirmeleri sağlanmıştır. Bu deney düzeneğinde kişilerin uzanmaları istenen hedefler, bilgisayar aracılığı ile dev TV ekranına oradan da katılımcıların kollarının altında bulunan aynaya yansıtılmıştır. Katılımcılar kollarını deney sırasında görememelerine rağmen, işaret parmaklarının uç noktasını gösteren bir körsır görmüşlerdir. Bu körsır bilgisayar ekranında fareyi oynattığımız zaman görünen körsır gibidir ancak deney düzeneğinde kullanılan körsir katılımcılar ellerini hareket ettirdikleri anda elleriyle birlikte hareket etmektedir. Körsır 1 cm çapında daire şeklinde gösterilmiştir. Katılımcıların yaptıkları uzanma hareketlerinin kinematik ve kinetik analizini yapmak için Flock of Birds elektromanyetik izleme sensörleri kullanılmıştır. Toplam dört adet sensör katılımcıların sağ ve sol alt-üst kollarına yerleştirilmiştir. Bu sensörler aracılığı ile eklemlerin yaptığı hareketler saniyede 103 nokta olacak şekilde kayıt edilmiştir.

Yukarıda da bahsedildiği gibi bu tez kapsamında üç farklı deney yapılmıştır. Bütün deneylerde, öncelikle katılımcıların genel olarak el tercih dağılımlarını belirlemek için hedefe ulaşırlarken sağ ve sol el arasında tercih yapacakları bir seçme ortamı sağlanmıştır. Daha sonra bu tercihlerin dağılımına göre bir grup katılımcıya sadece sol, diğer grup katılımcıya da sadece sağ ellerini kullanarak hedeflere ulaşmaları sağlanmıştır. Böylelikle sadece sağ ve sadece sol elini kullanan gruplardan elde edilen veriler kinematik ve kinetik analiz için kullanılmıştır. Her deneyde katılımcıların rahatlıkla ulaşabilecekleri toplam 32 adet hedef kullanılmıştır (Şekil 2). Bu hedefler 3.5 cm çapında daire şeklinde oluşmuştur. Bu hedeflere ulaşırken öncelikle sağ ve sol elin işaret parmaklarını belirlenmiş olan başlangıç noktalarına koymaları istenmiştir. Başlangıç noktalarının çapı da 2 cm olarak belirlenmiştir. Katılımcılar ellerini başlangıç noktalarına koydukları anda sesli bir uyarı ile ekranda görünen hedefe ulaşmaları istenmiştir. Hedeflerin yerleri ve sırası farklı olmak kaydıyla tek bir tane olacak şekilde katılımcılara gösterilmiş ve katılımcılara her iki ellerinden bir tanesini kullanarak gösterilen hedefe ulaşmaları istenmiştir. Ulaşma hareketi sırasında hızla ilgili bir uyarı veya geribildirim verilmemesine karşın, hedefe ulaşma süresi 1 sn olarak belirlenmiştir. Hedeflerin dağılımı ve dizilişi her bir katılımcı için kol uzunluklarına göre normalize edilmiştir. Katılımcılar her bir hedefe 10 tane uzanma hareketi yapmışlardır. Katılımcıların motivasyonunu arttırmak amacıyla hedefe ulaşma yerlerindeki duruma göre puanlar verilmiştir. Hedefin tam üstüne geldiklerinde 10, 1 cm dışına çıktıklarında 3 ve 2 cm dışına çıktıklarında da 1 puan verilmiştir. Bunun dışında puan verilmemiştir. İlk deneyde katılımcılar işaret parmaklarının ucunu gösteren körsırı görebiliyorlardı. Bundan dolayı hedefe ulaşma sırasında kollarının hareketi ile ilgili görsel geri bildirim deney sırasında sunulmuştur. Ancak ikinci deneyde ulaşma hareketi sırasında körsır ile ilgili görsel geri bildirim ortadan kaldırılmıştır. Katılımcılar başlangıç noktalarını ve hedefi görüyor olmalarına karşın elleri ile ilgili olan görsel bilgiye sahip değillerdi. Dolayısıyla proprioseptiv algılamanın el tercihini nasıl etkilediği bu deneyde ortaya konulmuştur. Son deneyde ise ilk deneyde olduğu gibi körsır ile ilgili görsel bilgi sunulmuş ancak katılımcı grubu elit eskrim sporcularından seçilmiştir.

Verilerin analizinde öncelikle katılımcıların el tercihi dağılımlarına bakılmıştır. Bu dağılama göre sağ ve sol elin istatistiksel olarak fazla ve her elin eşit derecede kullanıldığı hedefler belirlenmiştir. Belirlenen bu hedefler grup haline getirilmiştir. Daha sonra kinematik ve kinetik analiz yapılabilmesi için bu hedef grupları kullanılmıştır. Katılımcıların el tercihlerini etkileyen faktörleri belirlemek için hareketin doğruluğu, çizdiği eğri ve ne kadar enerji harcadığı ile ilgili kinematik ve kinetik değişkenlere bakılmıştır. Bunun yanında hız, ivmelenme ve yavaşlama gibi değişkenler de analiz edilmiştir. İstatistiksel analiz olarak da tekrarlı ölçümlerde ANOVA kullanılmıştır. ANOVA sonucunda istatistiksel olarak anlamlı farklılık bulunduğunda Post-hoc analiz olarak Tukey HSD (Honesty Significant Difference) testi kullanılmıştır. İstatistiksel anlamlılık düzeyi $p<0.05$ olarak belirlenmiştir. Bütün istatistiksel analizler JMP 8.0 istatistik paket programı kullanılarak yapılmıştır.

Sonuçlar

İlk deneyin sonuçlarına göre sporcu olmayan kişiler uzanma hareketi sırasında kolları ile ilgili görsel bilgiye sahip olduklarında, sağ ellerini genel olarak %68 oranında tercih etmişlerdir. Genel olarak katılımcılar vücutlarının sağ tarafı ve orta noktasında sağ ellerini baskın olarak kullanmışlardır. Ancak vücutlarının orta noktasını geçip sol tarafta da sağ ellerini belli oranda kullanmışlardır. Elde edilen sonuçlara göre vücudun sol tarafında ve orta noktasına hemen yakın olan yerin en üst yerinde bulunan hedefte de katılımcılar sağ ellerini sol ele göre daha fazla kullanmışlardır. Yine bu bölge yakınındaki 4 hedefte de sağ ve sol el eşit olarak tercih edilmiştir. Ancak bu bölgenin sol tarafına gidildikçe sol elin tercih edilme oranı artmıştır. Bu durumda, katılımcılar vücutlarının orta noktasını geçip sol tarafta da sağ ellerini kullanmışlardır. Sağ ve sol elin istatistiksel olarak fazla kullanılıp kullanılmadığına göre toplam 3 grup oluşturulmuştur; sağ elin fazla kullanıldığı hedefler, sol elin fazla kullanıldığı hedefler ve her iki elin eşit oranda kullanıldığı hedefler.

Kinematik ve kinetik analiz sonucunda bu hedef gruplarında her iki el arasında doğruluk açısından bir farklılık bulunmamıştır ($p>0.05$). Dolayısıyla doğruluk kişilerin el tercihini etkileyen bir faktör olarak görülmemiştir. Ancak uzanma hareketi sırasında elin çizdiği eğriyi belirleyen değişkene bakıldığında, istatistiksel olarak anlamlı farklılık tespit edilmiştir ($p<0.05$). Sağ elin fazla tercih edildiği hedef grubunda sağ elin çizdiği eğri sol ele göre istatistiksel olarak daha az bulunmuştur. Her iki elin eşit oranda tercih edildiği hedef grubunda, yani her iki elin istatistiksel olarak fazla tercih edilmediği grup da, her iki elin çizdiği eğri açısından da istatistiksel olarak anlamlı farklık bulunmamıştır. Sol elin fazla tercih edildiği grupta sol elin çizdiği eğri daha düşük olmasına rağmen bu istatistiksel olarak anlamlı bulunmamıştır. Bu yüzden, sağ elin fazla tercih edildiği grup ve her iki elin eşit tercih edildiği grup da elin çizdiği eğri değişkeni el tercihini açıklayabilen bir faktör olmaktadır. Hız anlamında sağ el sol tarafa giderken daha hızlı, sol el de sağ tarafa giderken daha hızlı uzanma hareketi yapmıştır. En son değişken olan uzanma hareketi sırasında ne kadarlık bir enerji harcandığını gösteren değişkene bakıldığında yine istatistiksel olarak anlamlı farklılık bulunmuştur. Elde edilen sonuçlara göre, sağ el sağ elin fazla tercih edildiği gruptaki hedeflere giderken daha az enerji harcamış, sol el de sol elin daha fazla tercih edildiği gruptaki hedeflere giderken daha az enerji harcamış. Her iki elin eşit oranda tercih edildiği grupta is yine uzanma hareketi sırasında sağ el daha fazla enerji harcamıştır. Aslında her iki elin eşit oranda tercih edildiği hedef grubuna uzanma sırasında sağ elin daha fazla enerji harcaması beklenen bir sonuç olmalıdır çünkü bu grupta yer alan hedeflerin hepsi de vücudun sol tarafında yer almaktadır ve sağ el açısından sol ele göre daha uzak mesafede yer almaktadırlar. Dolayısıyla sağ elin daha fazla enerji harcaması da çok normaldir. Ancak vücudun orta noktasında yer alan hedeflere bakıldığında (bu hedefler her iki ele eşit mesafe ve açıda yer almaktadırlar), bu hedeflere uzanırken sağ elin sol ele göre daha az enerji harcadığı bulunmuştur. Dolayısıyla uzanma sırasında harcanan enerjiyi belirleyen değişken de el tercihini açıklayan bir faktör olarak belirlenmiştir.

İkinci deneyde kişilerin sadece proprioseptiv algı ile hareket etmelerinin el tercihi üzerine etkisinin olup olmadığı araştırılmıştır. İkinci deneyde katılımcıların sağ ellerini tercih etme oranı genel olarak %60'a düşmüştür. Yani kişiler uzanma hareketi sırasında kolları ile ilgili görsel bilgiye sahip olmadıklarında sol ellerini tercih etme oranları artmıştır. İlk deneyde her iki elin eşit olarak tercih edildiği gruptaki hedef sayısı 4 iken, ikinci deneyde bu sayı 1'e düşmüş ve bu hedef vücudun orta noktasına en yakın olan en üst sırada yer alan hedef olarak belirlenmiştir.

El tercihine göre belirlenen üç gruptaki eller arasında doğruluk açısından farklılık olup olmadığına bakıldığında ise, ilk deneyden farklı olarak her üç grupta da sol elin doğruluğunun sağ ele göre daha iyi olduğu bulunmuştur. Elin çizdiği eğri değişkenine bakıldığında ise sağ elin fazla tercih edildiği grupta sağ elin daha düzgün bir eğri ile hareket ettiği, sol elin de sol elin daha fazla tercih edildiği grupta daha düzgün bir eğri ile hareket etiği görülmüştür. Son olarak da her iki elin eşit olarak tercih edildiği grupta, her iki elin de benzer eğri ile hareket ettiği gözlenmiştir. Dolayısıyla bu değişken ilk deneyde olduğu gibi el tercihini açıklayan bir değişken olarak bulunmuştur. Benzer olarak uzanma hareketi sırasında harcanan enerjiyi belirleyen değişken de elin çizdiği eğri değişkeninde olduğu gibi el tercihini açıklayan bir faktör olarak bulunmuştur.

Son olarak elit eskrim sporcularında yapılan deneyde, eskrim sporcularının sağ ellerini genel olarak %60 oranında tercih ettikleri bulunmuştur. Bu oran spor yapmayan kişilerde %68 olarak bulunmuştu. Yani uzun süreli antrenman yapan kişilerde sol el kullanma oranı bu tür antrenmanlara katılmayan ve spor geçmiş olamayan kişilere göre artmıştır. Aslında eskrim sporu yapan kişiler çoğunlukla baskın olan ellerini kullanmalarına rağmen, baskın olmayan ellerini de özellikle denge sağlamada kullanmaktadırlar. Dolayısıyla bu durum onların spor yapmayan kişilere göre sol ellerini daha fazla tercih etmelerini sağlamış olabilir. Son deneyde vücudun orta noktasına en yakın ve en üst sırada olan hedefte her iki elin tercihleri arasında istatistiksel olarak anlamlı farklılık bulunmamıştır.

El tercihini açıklamak için yine kinematik ve kinetik değişkenlere bakılmıştır. Sporcu olmayan grupta olduğu gibi, her 3 el tercih grubunda doğruluk açısından farklılık bulunmamıştır. Eskrim grubundaki sağ ve sol elin hızlarına bakıldığında, her iki elin de sporcu almayan gruba göre daha hızlı oldukları görülmüştür. Eskrim sporcularının hareket doğruluğu sporcu olmayan gruba göre benzer olmasına rağmen, hareket hızları daha yüksek olarak bulunmuştur. Elin çizdiği eğri değişkenine bakıldığında, sağ elin genel olarak üç tercih grubunda da sol ele göre daha düzgün gittiği gözlenmiş, ancak bu üç gruptan sağ elin fazla tercih edildiği grupta ve her iki elin aynı oranda tercih edildiği grupta istatistiksel olarak anlamlı farklılık bulunmuştur. Dikkat edilmelidir ki, eskrim yapan grubunda her iki el de spor yapmayan grubuna göre daha doğrusal bir uzanma hareketi sergilemiştir. Uzanma hareketi sırasında enerjiyi belirleyen değişkene bakıldığında, sol elin sol tarafta daha az enerji harcadığı, sağ elin de sağ tarafta daha az enerji harcadığı görülmüştür. Bu deneyde de elin çizdiği eğri ve enerji değişkeni, el tercihini etkileyen faktörler olarak belirlenmiştir.

Tartışma

Bu tezde; el tercihinin, kolun uzanması sırasında görsel bilgi varken ve bu bilgi ortadan kaldırıldıktan sonraki dağılımını belirlemek ve uzun süreli spor aktivitesinin bu tercih üzerine etkisi olup olmadığını belirlemek amacıyla 3 farklı deney yapılmıştır. Bunun yanında el tercihine etki eden faktörlerin neler olabileceği ile ilgili de veriler ortaya konulmuştur.

Yapılan ilk deneyde sporcu olmayanlarda uzanma sırasında kol ile ilgili görsel bilgi sağlanmış ve el tercihi dağılımına bakılmıştır. Elde edilen sonuç genel olarak sağ elin sol ele göre daha fazla tercih edildiğini göstermiştir. Bu sonuç alanda yapılan diğer çalışmalarla da benzerlik göstermektedir (Gabbard & Rabb, 2001; Mamolo ve ark., 2004; Stins, Kadar, & Costall, 2001). Kinematik ve kinetik veriler incelendiğinde ise el tercihine etki eden faktörlerin, elin hareket sırasında çizdiği eğri ve harcadığı enerji olduğu belirlenmiştir.

İlk deneyden elde edilen bulgulara göre elin çizdiği eğri ve harcadığı enerji sol el için daha iyi ve verimli olursa, sol elin tercih edilme oranının daha artabileceği hipotezini ortaya koymaktadır. Literatürde görsel bilgi olmadan yapılan hareketlerde sol elin sağ ele göre daha etkili olduğunu gösteren çalışmalar bulunmaktadır (Bagesterio & Sainburg, 2002; Goble, Hurvitz, & Brown, 2006; Goble & Brown, 2007; Lenhard & Hoffmann, 2007; Wang & Sainburg, 2006). Dolayısıyla yukarıda belirttiğimiz hipotezi test etmek için ikinci deneyde sporcu olmayan kişilerde hareket sırasındaki kolun pozisyonunu gösteren görsel bilgi kaldırılmıştır. Bu durumda sol elin tercih edilme oranı %8 oranında artmıştır. Bu durumun elin hareket sırasında çizdiği eğri ve harcadığı enerjiden kaynaklanıp kaynaklanmadığını belirlemek için kinematik ve kinetik verilere bakılmıştır. Elde edilen veriler, sol elin görsel bilgi olmadan yapılan hareketlerde daha fazla tercih edilmesinin nedeninin daha düzgün bir hareket eğrisi ve daha az enerji harcamasıyla ilişkili olduğunu göstermiştir. Dolayısıyla ilk deneyde olduğu gibi ikinci deneyde de bu iki değişken el tercihini açıklayan faktörler olarak bulunmuştur. Bunun yanında sol elin doğruluğunun sağ ele göre çok daha iyi olduğu da gözlemlenmiştir. Bu sonuç literatürdeki birçok çalışmanın sonuçları ile paralellik göstermektedir (Bagesteiro & Sainburg, 2002; Goble & Brown, 2008; Guiard, Diaz, & Beaubaton, 1983; Lenhard & Hoffmann, 2007; Sainburg, 2002; Sainburg & Wang, 2002). Genel olarak birinci ve ikinci deneyden elde edilen sonuçlar el tercihinin sağ ve sol el arasındaki sensorimotor performanstan kaynaklandığını göstermektedir.

Bu tez kapsamında yapılan son deneyde ise, uzun süreli yapılan egzersizlerin el tercihini etkileyip etkilemediğine bakılmıştır. Bazı araştırmacılar, el tercihinin sabit ve değişmeyen bir özellik olmadığını ve spor veya müzik alanında yapılan egzersizlerin bunu etkileyebileceğini önermişlerdir (Elbert ve ark., 1995; Mikheev et al., 2002). Bu yüzden üst düzeyde yapılan egzersizlerin her iki elin de performansını olumlu yönde etkileyebileceği söylenebilir. Bu durumu test etmek için son deneyde elit düzeyde eskrim sporu yapan kişilerin el tercihleri araştırılmıştır. Deney sonucunda eskrim sporcularının normal kişilere oranla sol ellerini %8 oranında daha fazla tercih ettikleri bulunmuştur. Bu sonuçtan, elit düzeyde yapılan antrenmanların sol elin performansını da geliştirdiği bu yüzden sporcu olmayanlara oranla sol elin daha fazla tercih edildiği görülmüştür. Sporcu olmayanlarda olduğu gibi, eskrimcilerde de hareket sırasında elin çizdiği eğri ve ne kadar enerji harcadığı el tercihini açıklayan faktörler olarak bulunmuştur. Sporcu olmayan grupla karşılaştırıldığında, eskrim sporcularının sporcu olmayan gruba göre daha hızlı uzanma hareketini yapmış olmalarına rağmen, hareketi aynı doğrulukta ve daha düzgün bir eğri ile yaptıkları görülmüştür. Bunun da uzun süreli yapılan egzersizlerden kaynaklandığı söylenebilir.

Sonuç olarak el tercihinin her iki el arasındaki sensorimotor performanstan kaynaklandığı bulunmuştur. Bu durumun aynı zamanda görsel ve proprioseptiv algılamadan da etkilendiği görülmüştür. Yapılan en son deneyde de el tercihinin uzun süreli yapılan egzersizlerden etkilendiği bulunmuştur.

Sonuç ve Öneriler

Literatürde el tercihi ile ilgili yapılan çalışmaların çoğu daha çok sayısal olmayan verilere dayanmaktadır. Bu tez kapsamında sayısal veriler elde edilerek yapılan detaylı analiz sonucunda el tercihinin sensorimotor performans ile ilişkili olduğu ve aynı zamanda uzun süreli egzersizlerden etkilendiği bulunmuştur. Dolayısıyla, sağlak olan kişilerin sağ ellerini vücudun orta noktasında ve orta noktasının hemen sol tarafında kullanmalarının nedeni günlük hayattaki alışkanlıktan değil, sağ elin o bölgelere uzanma gerektiren hareketleri daha etkili yaptığından kaynaklanmaktadır. Bu da kişilerin aktif bir tercih yaptıklarını göstermektedir. İleride yapılacak olan çalışmalarda bu aktif tercihi etkileyebilecek farklı faktörlerin olup olmadığının araştırılması önem taşımaktadır.

El tercihi ile ilgili yapılan çalışmalarda çocuklardaki durumun ne olduğuna da bakılmıştır. Ancak yaşlılardaki durumu bildiren çalışma bulunmamaktadır. Çok yakın zamanda, Przybyla ve arkadaşları (2011) yaşlılarda motor asimetride bir azalma olduğunu bulmuşlardır. Yani yaşlılıkta sağ ve sol el arasındaki performans farklılıkları azalmaktadır. Bu yüzden, yaşlılarda motor asimetrideki bu azalmanın el tercihini nasıl etkilediğini araştırmak da önemlidir.

Bu tez kapsamında uzun süreli yapılan egzersizlerin el tercihini etkilediği bulunmuştur. Uzun süreli egzersiz yapan grup olarak eskrim sporcuları seçilmiştir. Eskrimde sporcular genelde sağ ellerini kullanmaktadırlar. Ancak sol elleri de özellikle denge için kullanılmaktadır. Ancak bunun yanında her iki elin de simetrik olarak kullanılan spor dallarında el tercihini araştırmak ve yapılan farklı türden egzersizlerin el tercihini nasıl etkilediğini belirlemek de önem taşımaktadır.

E. CURRICULUM VITAE

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Feedback effects on spatial memory

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Publications:

Papers Published in Refereed National Journals:

Akpınar, S., Mirzeoğlu, N. (2006). Kinematic Analysis of Overarm Throws in Handball Players of Different Levels. Spormetre, 4(1), 19-23.

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National Congress and Presentations:

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Akpınar, S., Kirazcı, S., & Aşçı, F.H. (2006). The Validity and Reliability Study of Group Environment Questionnaire. 9th International Sports Science Congress, Muğla, Turkey.

Projects:

2007	Kirazcı, S. & **Akpınar, S.** The Effect of Different Feedback Types on Spatial Memory Among Blind And Sighted People. BAP-06-05-00-01

Congress Participations:

June 2010	15th European College of Sport Science, Antalya-Turkey
November 2010	40th Annual Neuroscience Meeting, San Diego, CA, USA
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