Mathematical Biosciences and Engineering

Mathematical Biosciences and Engineering, 16 (3): 1611–1624.
DOI: 10.3934/mbe.2019077
Received: 13 November 2018
Accepted: 29 January 2019
Published: 26 February 2019

http://www.aimspress.com/journal/MBE

Research article

Comparison of dominant hand to non-dominant hand in conduction of reaching task from 3D kinematic data: Trade-off between successful rate and movement efficiency

Xiang Xiao[1,2,†], Huijing Hu[3,†], Lifang Li [1,4,†] and Le Li[1,*]

[1] Department of Rehabilitation Medicine, First Affiliated Hospital, Sun Yat-sen University, Guangzhou, China
[2] Department of Rehabilitation Medicine, Luo Hu peoples' hospital, Shenzhen, China
[3] Guangdong Work Injury Rehabilitation Center, Guangzhou, China
[4] Department of Rehabilitation Medicine, Seventh Affiliated Hospital, Sun Yat-sen University, Shenzhen, China

* **Correspondence:** Email: lile5@mail.sysu.edu.cn; Tel: +862087608536.

† These three authors contributed equally.

Abstract: This study aimed to investigate the effects of handedness on motion accuracies and to compare 3D kinematic data in reaching performance of dominant and non-dominant hand with the influence of movement speed and target locations. Twelve healthy young adults used self-selected and fast speed to reach for three different target locations as follows: frontal, ipsilateral and contralateral to the performing hand, with equal distance. Both hands were tested and kinematic parameters were recorded by 3D motion analysis system. Successful rate, reach path ratio, mean and peak velocity, the timing of peak velocity and ROM of joints were analyzed. Reach path ratio was smaller when using the dominant hand ($p < 0.01$) and fast speed ($p < 0.01$) to perform the movement, but the successful rate of the dominant hand was lower than non-dominant hand during fast speed reaching (99.1% vs 100%). Contralateral movement had lower velocity than the other two target locations, while velocity did not vary between non-dominant and dominant hand. The timing of peak velocity occurred significantly later for fast speed movements ($p < 0.01$). Trunk rotation was significantly smaller when using the dominant hand, fast movement speed or reaching to the ipsilateral target. The ROM of elbow and wrist flexion-extension decreased in contralateral reaching.

The performance of the dominant hand and/or fast speed movements was more efficient with straighter hand path and less trunk rotation, but the successful rate decreased in dominant hand during fast speed movements. The timing of peak velocity occurred later during fast movement in both hands indicating a decreased feedback phase. Target location can influence movement strategy as reaching to contralateral target required more proximal movements and ipsilateral reaching used more distal segment movements.

Keywords: handedness; kinematic; motor strategy; upper extremity; reaching

1. Introduction

Asymmetries of the hemispheres have inspired a great deal of research and evidences have shown the advantage of the hemisphere contralateral to the preferred arm for both preferred and nonpreferred arm movements [1]. For example, individuals with left hemisphere injury resulted in an impairment of making precise, independent movements of both hands, while right hemisphere damage was more likely to affect only the contralateral left hand [2]. Although hemisphere asymmetries have been demonstrated in various ways, the current knowledge from imaging technology limits in evaluation of movement in dynamic condition, and brain stimulation technology also impacts by the motion artifact when interpreting the results [3]. Asymmetries in upper limb performance are commonly known as handedness [1] and it was used to describe as a “preference” for using dominant/preferred hand to perform tasks [4]. There is an increased number of studies that explored handedness as asymmetries of the hands in sensorimotor processing [5]. It has been proved dominant arm advantages in controlling limb segment during fundamental tasks such as reaching [6]. The quantification of arm differences in motor output is one of the most traditional approaches to the study of handedness and dynamic performance of the hands during motor task.

Reaching is a fundamental component of many daily activities, requiring the coordination of multiple upper limb joints, thus is one of the most commonly used movement to study upper limb function [7]. People after neurological damage such as stroke have deficits of upper limb movement and the impairment affects their motor task. Clinical scales such as Fugl-Meyer Assessment (FMA) has been used to evaluate motor function but the assessment lacks sensitivity to detect changes in motor performance of each joint. These scales could not distinguish between motor function improvement and compensation strategies, and the assessment results might be affected by observer bias [8]. This may be due to the functional activities of upper limb are plenty and vary greatly [23]. Therefore, objective and quantitative evaluation of three-dimensional (3D) movement in the upper extremity is important and those evaluations would also be valuable to explore the mechanism behind different movement performance.

Kinematic analysis of the upper extremity end-point and joint movement is a quantitative and objective evaluation of sensorimotor function [8,9] . The combination of smoothness, peak velocity, movement time and joint coordination during movement could be used to explain the clinical changes in stroke survivors. Joint angle coordinate strategy was used to investigate the planning of the central nervous system around the recruitment and coordinate of the upper-limb joints [10], while endpoint coordinate strategy explored the spatiotemporal parameters of the endpoint (e.g.

hand or finger) during reaching. Trunk compensatory movement has been considered an important factor in studies of reaching performance [11] and used for distinguishing the severity of motor impairment [12].

Motor control of goal-directed upper limb movement can be divided into phases such as target location, movement planning and movement execution [13]. Target locations can influence limb choice of reaching in healthy subjects and hemiplegic patients [14]. Speed-accuracy trade-off has also been analyzed in target-directed movement and it has mostly been regarded as a conflict [15]. However, some studies had shown that the speed and accuracy effects were independent to each other [16,17]. DeJong and coworkers even found better movement quality during faster movement after stroke because reach path was straighter and peak thumb-index finger separation was greater when performing reach–grasp–lift movements [18]. The mechanisms of motor deficits on reaching after neurological impairments are still hard to understand and handedness should be explored as it may be one of the factors that interfere with the understanding of the deficits. In addition, even in healthy subject, the accuracy and efficiency of dominant and non-dominant hand during reaching at different target location with different speed are still not been fully studied. The information about the influence of movement speeds and target locations is helpful to the design and conduction of rehabilitation intervention for upper limb function recovery after neurological insult, such as stroke. Therefore, the objectives of this preliminary study were to compare kinematic data in reaching performance of dominant and non-dominant hand in healthy adults and to investigate handedness on motion accuracies and efficiencies with the influence of movement speed and target locations. The findings of current study might help us to understand the mechanism behind different performances of upper limb movement and then facilitate the development of rehabilitation strategy on motor control of patients after stroke.

2. Methods

2.1. *Subjects*

Twelve healthy subjects (5 males, 7 females, with the age of 21.8 ± 2.2) without neurological disease, upper limb musculoskeletal injury or pelvic dysfunction were participated in this study. All the recruited subjects were undergraduate students and were right-handed with the assessment of the Edinburgh Handedness Inventory [19]. Then the right hand is deemed as dominant hand and the left hand is non-dominant hand. This study had been approved by Ethics Committee of the First Affiliated Hospital of Sun Yat-Sen University, and all subjects provided informed consent before the experiment.

2.2. *Procedures*

Three bells were put on the table with different locations: In front of the tested shoulder, ipsilateral and contralateral to the performing hand (Figure 1A) and with 75% of the length from axilla to the styloid process of the radial bone with the elbow in full extension position [20]. Subjects sat and kept an upright posture during the procedure on a 45 cm-height chair and in front of a 75 cm-height table with their tested shoulder, hand and frontal bell in a line, and the hand was first placed on a fixed area of the table edge (Figure 1B). The subject kept the same sitting position when the tasks changed from non-dominant to dominant hand.

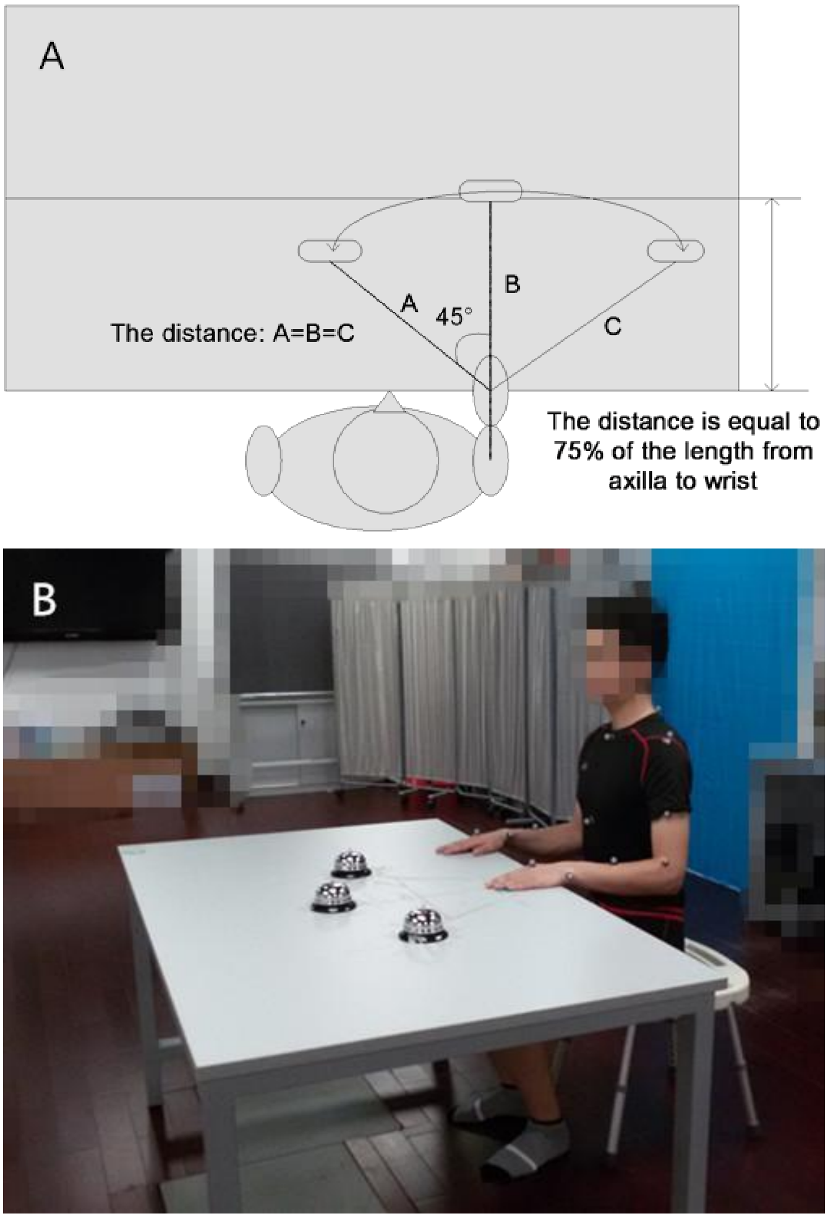

Figure 1. (A) Three bells were put on the table with different locations: in front of the tested shoulder, ipsilateral and contralateral to the performing hand and the distance is equal to 75% of the length from axilla to wrist. (B) Subjects sat comfortably on a 45cm-height chair and in front of a 75 cm-height table with their tested shoulder, hand and frontal bell in a line, and the hand was first placed on a fixed area of the table edge. All the recruited subjects are right-handed.

During the experiment, the instructor first demonstrated one trial of reaching task using self-selected speed to touch all three targets with the sequence of contralateral, frontal and ipsilateral position. Participants were then asked to perform the same practice trial of reaching task. This practice was used to help the subject get familiar with the distance of reaching, the location of bell, and the ringing sound of the bell. One reaching movement was defined as hand starting from the table edge, touching the center button of the bell and ringing it successfully then return to the starting position of table edge. Then the subject was asked to complete continuously nine reaching movements with self-selected speed in same pre-settled sequence as practice at three different locations for three times. These nine reaching movements comprised to a single reaching task and the subject was required to complete three repeated reaching tasks well before they took break and rested at least 1 minute in between reaching tasks to avoid fatigue. After self-selected reaching, the subject was given a fast speed (i.e., as quickly as possible) practice trial. Then the subject performed fast speed movements within 15 seconds and the instructor gave verbal order of stop to the subject when time is up. The number of movements and errors were recorded for calculating successful rate. The subject executed three fast reaching tasks following with same sequence of target location as those of the self-selected speed. They were given enough break between tasks.

2.3. Data analysis

Kinematic data of upper limb segments and the trunk were collected by a 3D motion analysis system (VICON MX13, Oxford, UK) with six cameras (frame rate = 100 Hz). Marker placement followed Plug-in Gait Upper Body Models. In details, nineteen 15 mm infrared-reflective markers were taped to the skin overlying bony landmarks of the trunk and both upper limbs, including the spinous processes of the 7th cervical vertebrae and the 10th thoracic vertebrae, jugular notch where the clavicles meet the sternum, xiphoid process of the sternum, the middle point between the superior and inferior angles of the scapula, the acromioclavicular joint of both sides, lateral epicondyle of elbows, both thumb side and pinkie side of the wrist joints, the dorsum of the hands below the second metacarpal heads, and the middle of the upper arms and forearms. Local coordinate system was constructed for each joint based on these bony landmarks, and the movements of the joint were recorded in three dimensional planes described as flexion-extension, adduction-abduction and rotation movements. Kinematic models were built and were responsible for the definitions of the rigid body segments, and the calculations of joint angles between these segments. The positions of the rigid segments were defined on a frame-by-frame basis. Each segment was defined by an origin in global (laboratory) coordinates, and three orthogonal axis directions. All segment axis systems were right-handed systems. Outputs required from the modelling were then calculated and the output angles for all joints are calculated from the YXZ cardan angles derived by comparing the relative orientations of the two segments.

For output of the reaching tasks, errors were recorded if the participant did not complete the reaching movement accurately (i.e., did not complete the whole movement of reaching the bell from the start position and coming back to the original point successfully). The successful rate was calculated as the percentage of the successful reaching movements to total movements. The movement trajectory of the hand marker from the starting point to the end point (which is the same as starting point) was rebuilt in the 3D space using MATLAB. Reach path ratio [21] was calculated as the length of the hand marker travel trajectory divided by the straight distance of the two points and used to define the movement smoothness [22]. A smaller ratio near 1 represented a straighter movement path and a smoother and more efficient movement.

Peak and mean velocity of the hand marker were calculated and velocity profiles were drawn in MATLAB. The timing of peak velocity was determined as the percentage of movement duration when the peak velocity occurred. A higher one indicated a longer acceleration phase. The maximum and minimum articular range of motion (ROM) was calculated for the trunk, elbow and wrist joint [23]. The trunk rotation was the trunk movement in the horizontal plane which we used to reflect trunk involvement during the reaching movement.

2.4. Statistical analysis

IBM SPSS statistics 20 was used for statistical analyses, and $p < 0.05$ was set as the criterion for statistical significance. All parameters were firstly analyzed using a multivariate 2 (two sides) × 2 (two speeds) × 3 (three locations) repeated ANOVA with a Bonferroni post hoc test in all factors as within-subject ones. A two-way or one-way repeated ANOVA was used for secondary testing when factor interaction existed.

3. Results

Subjects completed the task without any mistake during the self-selected speed reaching task using the dominant and non-dominant hands. In fast speed movements, errors could be found when using dominant hand, but not on non-dominant hand. More specifically, four participants of the twelve made mistakes once when using dominant hand to perform fast speed reaching (i.e. touch the wrong bell, did not return but directly go for next bell, miss the bell), while no mistakes were found during other conditions. The successful rate of the non-dominant hand was 100%, and the dominant hand was 99.1% during fast speed reaching.

Figure 2 presented the movement trajectory and velocity profile of self-selected speed reaching to three different location targets using both dominant and non-dominant hand. The movement paths were smooth curves from the starting point to the end point with consistent shape regardless of target location and the side of hand (Figure 2A). The velocity curve was a bell-shaped profile with an acceleration and a deceleration phase, and the value of dominant hand was slightly higher than non-dominant hand Figure 2B).

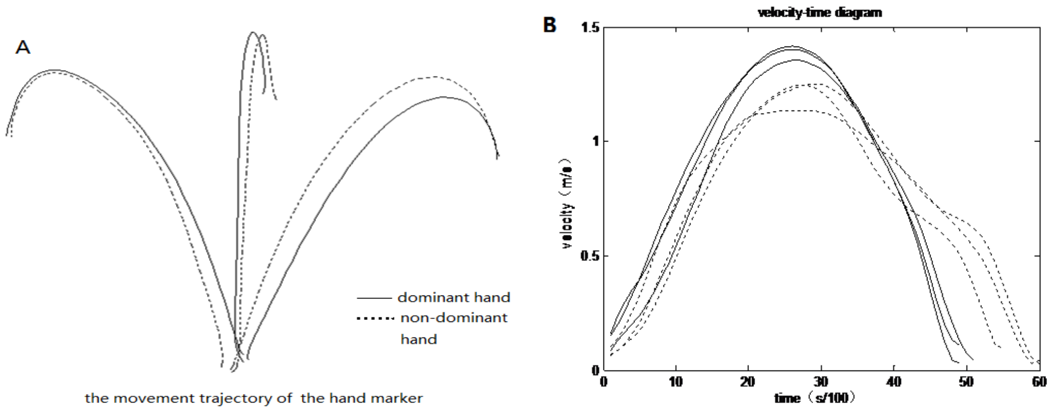

Figure 2. Reaching movements of dominant (solid line) and non-dominant (dotted line) hand in one subject using self-selected speed to three different location targets. (A) the movement trajectory of the hand marker, (B) the velocity profile of the hand marker.

Figure 3 showed reach path ratio, peak velocity, mean velocity and time percentage of peak velocity of the non-dominant and dominant hand when using self-selected and fast speed to reach contralateral, frontal and ipsilateral targets. Statistical results were presented in Table 1, including main effect and interaction of the side of hand, movement speed and target location for these kinematic parameters.

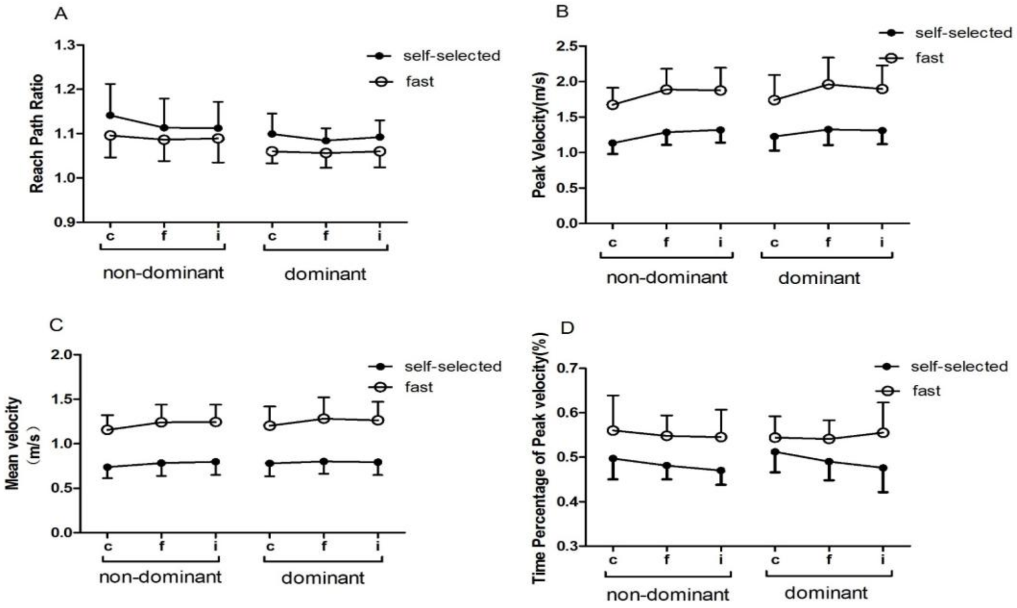

Figure 3. Effect of different movement speeds and target locations using non-dominant and dominant hand. (A) Reach Path Ratio, (B) Peak Velocity, (C) Mean Velocity and (D) Time Percentage of Peak Velocity were shown for the non-dominant and dominant hand when using self-selected (filled circle) and fast speed (open circle) to reach contralateral (c), frontal (f) and ipsilateral (i) targets. The error bar represents 1 standard deviation (SD).

Table 1. ANOVA tables for the main effect and interaction for kinematic parameters of the reaching tasks.

	Reach Path Ratio		Peak velocity		Mean velocity		The timing of peak velocity	
	F	P	F	P	F	P	F	P
Main effect								
hand	10.20	0.009*	1.06	0.324	0.97	0.345	0.13	0.727
speed	23.64	0.001*	60.18	<0.001*	78.44	<0.001*	33.23	<0.001*
location	3.07	0.067	61.47	<0.001*	19.22	<0.001*	3.53	0.047*
Factor interaction								
hand*speed	0.01	0.91	0.04	0.842	0.19	0.670	1.17	0.303
hand*location	1.34	0.28	3.27	0.057	2.56	0.100	0.25	0.783
speed*location	2.36	0.12	4.97	0.017*	5.11	0.015*	4.06	0.032*
hand*speed*location	0.44	0.65	0.46	0.638	0.23	0.796	1.83	0.184

*$p < 0.05$.

Reach path ratio was significantly smaller in dominant hand ($p < 0.01$) than non-dominant hand and was significantly smaller in fast speed ($p < 0.01$) movement than self-selected speed (Table 1). The ratio was higher when reaching to the bell positioned on the contralateral side than the other two locations during self-selected speed movement, but the influence of locations did not reach statistical significance when moving fast. The impact of all the factors to the peak and mean velocity were consistent. Participants could increase their mean velocity when asked to perform fast reaching, and target location also influenced the velocity, indicated by a significant speed×location interaction. The peak and mean velocity did not vary between non-dominant and dominant hand ($p = 0.324$; $p = 0.345$). Contralateral movement had lower velocity than the other two target location movements during both self-selected and fast speed movements.

The timing of peak velocity was influenced by movement speed and target location with a significant speed × location interaction. Peak velocity occurred significantly later for fast speed movements compared with the self-selected speed one in all the locations. The timing of peak velocity did not vary among different target locations during fast speed movements, but was significantly later in contralateral and frontal reaching than ipsilateral one during self-selected movements. The timing of peak velocity was not significantly different between non-dominant and dominant hand ($p = 0.727$).

Trunk rotations were shown in Figure 4 during the reaching tasks. A 3-way ANOVA was first used (Table 2), and then followed by a 2-way ANOVA (Table 3) as factor interaction existed. Trunk rotation was significantly smaller when using dominant hand ($p = 0.034$) or fast speed ($p = 0.002$) to perform the movement, and it also decreased when reaching to the ipsilateral target. Although the ROM of trunk rotation was higher in frontal reaching than contralateral one, the difference did not reach the statistically significant level.

Table 2. ANOVA tables for the main effect and interaction of ROM of the upper extremity and trunk during the reaching tasks.

	Elbow flexion-extension		Wrist flexion-extension		Trunk rotation	
	F	P	F	P	F	P
Main effect						
hand	0.159	0.698	1.151	0.306	5.594	0.034*
speed	5.432	<0.040*	6.459	0.027*	14.275	0.002*
location	13.123	<0.001*	33.270	<0.001*	45.650	<0.001*
Factor interaction						
hand*speed	3.883	0.074	7.583	0.019*	2.170	0.165
hand*location	6.494	0.006	0.007	0.993	4.370	0.023*
speed*location	2.815	0.082	0.663	0.525	0.838	0.444
hand*speed*location	11.046	<0.001*	0.057	0.945	0.037	0.964

*$p < 0.05$.

Table 3. ANOVA tables of non-dominant and dominant hand for the main effect and interaction of movement speed and target location for ROM of the upper extremity and trunk during the reaching task.

		Elbow flexion-extension		Wrist flexion-extension		Trunk rotation	
		F	P	F	P	F	P
Non-dominant hand	speed	9.31	0.011*	0.66	0.434	11.24	0.006*
	location	5.52	0.011*	24.89	<0.001*	25.60	<0.001*
	speed*location	2.06	0.151	0.11	0.897	0.59	0.563
Dominant hand	speed	2.47	0.144	28.53	<0.001*	7.88	0.017*
	location	22.02	<0.001*	13.08	<0.001*	39.14	<0.001*
	speed*location	14.99	<0.001*	0.41	0.667	0.19	0.830

*$p < 0.05$.

Fast speed movements increased the ROM of elbow flexion-extension significantly in the non-dominant hand ($p = 0.011$), while the influence of location was not significant using Bonferroni for secondary testing. In dominant hand, the elbow ROM was significantly higher in frontal and ipsilateral than contralateral reaching when moving fast, and only ipsilateral was higher than contralateral when using self-selected speed. The ROM of wrist flexion-extension was smaller in contralateral reaching than frontal and ipsilateral in the two movement speed conditions and in both non-dominant and dominant hand, while the influence of movement speed was only significant in dominant hand.

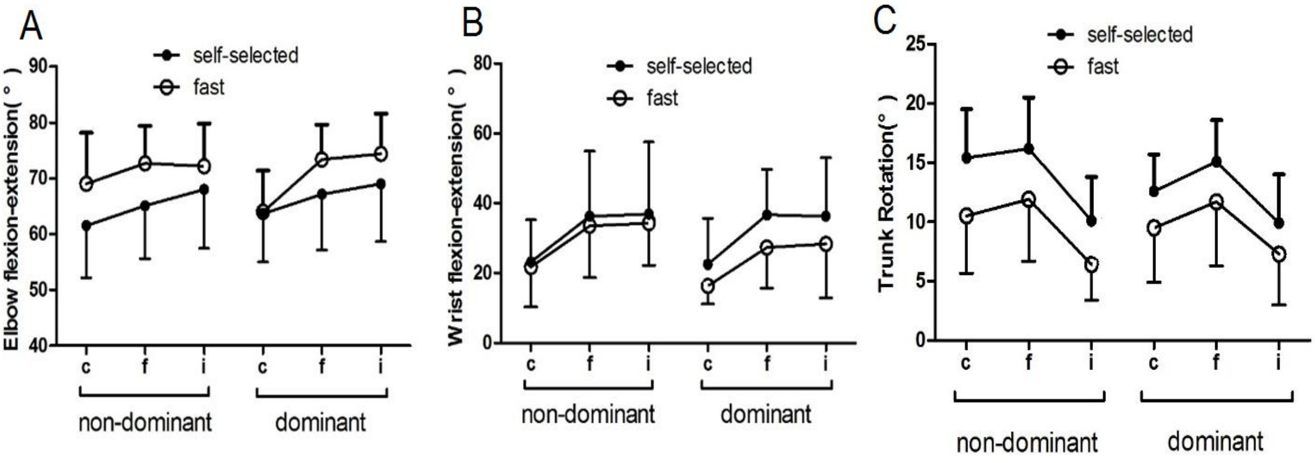

Figure 4. Articular range of motion of the upper extremity and trunk during reaching with different movement speeds and target locations using both hands. (A) Elbow flexion-extension, (B) Wrist flexion-extension and (C)Trunk rotation were shown for the non-dominant and dominant hand when using self-selected (filled circle) and fast speed (open circle) to reach contralateral(c), frontal(f) and ipsilateral(i) targets. The error bar represents 1 standard deviation (SD).

4. Discussion

This study used successful rate and kinematic parameters such as reach path ratio, velocity and ROM of the upper extremity and trunk to compare reaching performance of dominant and non-dominant hand and investigate the effect of movement speed and target location on reaching task. There was a trade-off effects since more efficient movement was found in dominant hand or fast speed reaching as hand path was straighter and trunk rotation was smaller, but the successful rate decreased in dominant hand during fast speed movements. Different ROM of the upper extremity and trunk indicated that motor strategy might vary with target locations.

Dominant hand reaching was more efficient with straighter movement path (lower reach path ratio) and smaller trunk rotation, indicating better motor control in this hand and asymmetries of dominant and non-dominant hand during the movement. Sainburg and Kalakanis also found that straighter hand path trajectories were achieved in dominant arm reaching through a more efficient inter-limb torque pattern. However, mistakes were found when using dominant hand to perform fast speed reaching with successful rate of 99.1% vs 100% of non-dominant hand. Bagesteiro and Sainburg proved that the non-preferred arm/hemisphere system play a specialized role for sensory feedback-mediated error correction [24]. In their study, a 2 kg mass was attached to subjects and they had no knowledge of the added load, nor can they view their limb or the mass. There was no difference in final position accuracy between loaded and baseline trials for the non-dominant hand, while the dominant hand produces large and systematic overshoots of final position. This indicated the advantage of the non-dominant hand in sensory feedback mediated error correction. These results were consistent with a dynamic dominance hypothesis (open/closed loop model) of motor Lateralization That Account For A Series Of Experiments Studying Handedness In Different Conditions [1,25]. This hypothesis suggests that the left hemisphere (dominant right arm) is associated with open-loop control and specialized for processes of predictable dynamic conditions, making movements to be mechanically efficient and have ballistic trajectories. In contrast, the right hemisphere is associated with closed-loop control (i.e. relatively feedback dependent), and often shows better accuracy in achieving a specific position, particularly when the ongoing movement is perturbed.

The difference of movement velocity between the dominant and non-dominant hand was not significant during both self-selected and fast speed movements, which was in accordance with previous studies [26,27]. Sainburg and colleagues had also found that during rapid upper limb movement which required similar displacements at elbow joints, non-dominant arm movement required greater elbow extension than dominant arm [6,28]. Their movement task was like the fast speed reaching to the contralateral target in which the ROM elbow was small, and our study consistently showed smaller ROM of elbow flexion-extension in dominant hand than non-dominant (paired-samples T Test; $p = 0.02$). These results could not be extended to other experiment conditions, and it might because different movement strategies were required during varying upper limb movement tasks.

Movement quality improved during fast speed movements: reach path was straighter, peak and mean velocity was higher and trunk rotation was smaller, and better movement performance was also found during faster upper limb task in stroke patients [18,29]. The timing of peak velocity occurred later during fast movement indicating the reduction of deceleration phase. This was consistent with previous findings that the duration of the deceleration phase was extended as accuracy demands increased, which could be explained by the increase of feedback control [30,31]. The ROM elbow flexion-extension in non-dominant hand and wrist flexion-extension decreased in dominant during fast speed movements. Trunk rotation was smaller when moving fast than self-selected speed in both hands. This inclination of increasing in elbow flexion-extension and decreasing in trunk movement was also found in previous study in normal people when comparing with stroke patient [23]. This might suggest that better movement strategy was used in fast speed movements as the same strategy was used in control subjects instead of the hemiplegic patients.

Movement to the contralateral target had lower velocity than the other two target locations during both self-selected and fast speed movements, and it had higher reach path ratio during self-selected speed reaching, while the influence was not significant when moving fast. The differences between contralateral and ipsilateral reaching were explored in both healthy subjects [32,33] and stroke patients [14,29,34,35], revealing several advantages for ipsilateral reaching such as shorter movement duration, higher movement velocity, increased smoothness. A popular interpretation of these advantages is that ipsilateral reaching is related to interhemispheric processing [28,36]. For example, a target on the left side would be processed in the right visual cortex and the same hemisphere controls the motor output of left hand reaching. In contrast, contralateral reaching is associated with interhemispheric cooperation. But Carey and colleagues challenged this model by comparing antipointing movements with pointing movement and proposed that hemispatial movement differences could be explained by the biomechanical factors in the movement execution [32]. In our study, trunk rotation was larger in contralateral reaching than ipsilateral one, while elbow and wrist flexion-extension increased in ipsilateral reaching. This might indicate that reaching to contralateral target required more proximal control strategies and ipsilateral reaching used more distal segment movements. The ROM of trunk rotation was higher in frontal and contralateral reaching than ipsilateral one, which is reasonable and consistent with previous study [11]. In their study, the trunk rotation changed little across healthy subjects and consistent variations were found with distance, height and direction, indicating that the pattern of trunk rotation had a functional role and participated in the kinematic chain for reaching.

This study has some limitations which limits the interpretation and generalizability of the data. First, as a preliminary study we first only recruited healthy young adults to participant and tried to demonstrate the feasibility of the protocol been applied. In the future study, we will recruit persons after stroke with different stages i.e. acute, subacute, and chronic stages to evaluate the motor control performance. Second, all the recruited subjects happened to be right-handed and we focused on the differences of the kinematic data and compared the performance of dominant and non-dominant hands, but did not try to link the differences with the Handedness Inventory results of sub-groups. This might be a good research question to further analysis with large sample size of sub-groups based on different Handedness Inventory decile values to reveal the underlying differences. Third, in order to make the comparison directly for speeds, we used the same sequence of target position (i.e. contralateral, frontal and then ipsilateral position) for these two speeds, although the sequence of the hand is randomized for different subjects. In order to avoid the fatigue and the bias effects of fast speed to self-selected speed movement, we performed self-selected speed movements first and give enough rest then move to fast speed reaching. Therefore, we focus on comparison of a task for hand and speed, especially for the successful rate, and avoid the complex of position sequence which may cause to involve much more cognitive ability of subject rather than motor function. The last point is that electrophysiology information such as surface EMG should be added to further investigate the coordination of muscles and to understand the motor control strategy [37,38]. In addition, morphology parameters of muscle could influence reaching movement and muscle architecture evaluated from ultrasound technology [39,40] might be helpful to reveal the biomechanical mechanism of reaching after stroke.

5. Conclusions

Our findings revealed that the performance of the dominant hand and/or fast speed movements was more efficient with straighter hand path and less trunk rotation, but unsuccessful reaching task was observed using dominant hand during fast speed movements. This may due to the left hemisphere (dominant arm) is specialized for making movements to be mechanically efficient and have ballistic trajectories, while the right hemisphere shows better performance in error correction and achieving a specific position. Target location can influence movement strategy as reaching to contralateral target required more proximal movements and ipsilateral reaching used more distal segment movements. These findings could help to understand the motor control strategy during reaching and might be useful to facilitate the design of suitable training protocol for motor recovery of upper limb in stroke survivors.

Acknowledgement

This study is supported by Natural Science Foundation of China (No.31771016, 81702227), Science and Technology Planning Project of Guangdong Province (No. 2017A020211002, 2017B010110015) and Natural Science Foundation of Guangdong Province, China (No. 2015A030313139). This project is also partly supported by Royal Society International Exchanges grant (No. 170168), UK.

Conflict of interests

The authors declare that they have no competing interests.

References

1. D. J. Goble and S. H. Brown, The biological and behavioral basis of upper limb asymmetries in sensorimotor performance. *Neurosci. Biohehav. R.*, **32**(2008), 598–610.
2. B. Hanna-Pladdy, J. E. Mendoza and G. T. Apostolos, et al., Lateralised motor control: hemispheric damage and the loss of deftness, *J. Neurol. Neurosurg. Psychiatry*, **73**(2002), 574–577.
3. G. A. Ghacibeh, R. Mirpuri and V. Drago, et al., Ipsilateral motor activation during unimanual and bimanual motor tasks, *Clin. Neurophysiol.*, **118**(2007), 325–332.
4. M. P. Bryden, Measuring handedness with questionnaires, *Neuropsychologia*, **15**(1977), 617–624.
5. R. Sainburg, Evidence for a dynamic-dominance hypothesis of handedness, *Exp. Brain Res.*, **142**(2002), 241–258.
6. R. L. Sainburg and D. Kalakanis, Differences in control of limb dynamics during dominant and

nondominant arm reaching, *J Neurophysiol.*, **83**(2000), 2661–2675.

7. J. M. Wagner, C. E. Lang and S. A. Sahrmann, et al., Sensorimotor impairments and reaching performance in subjects with poststroke hemiparesis during the first few months of recovery, *Phys. Ther.*, **87**(2007), 751–765.
8. L. Van Dokkum, I. Hauret and D. Mottet, et al., The contribution of kinematics in the assessment of upper limb motor recovery early after stroke, *Neurorehabil. Neural Repair,* **28**(2013), 4–12.
9. B. Hingtgen, J. R. McGuire and M. Wang, et al, An upper extremity kinematic model for evaluation of hemiparetic stroke, *J. Biomech.*, **39**(2006), 681–688.
10. C. Bosecker, L. Dipietro and B. Volpe, et al, Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke, *Neurorehabil. Neural Repair,* **24**(2010), 62–69.
11. J. V. G. Robertson and A. Roby-Brami, The trunk as a part of the kinematic chain for reaching movements in healthy subjects and hemiparetic patients, *Brain Res.*, **1382**(2011), 137–146.
12. S. K. Subramanian, J. Yamanaka and G. Chilingaryan, et al., Validity of movement pattern kinematics as measures of arm motor impairment poststroke, Stroke, **41**(2010), 2303–2308.
13. R. J. Van Beers, P. Haggard and D. M. Wolpert, The role of execution noise in movement variability, *J Neurophysiol.*, **91**(2004), 1050–1063.
14. M. Levin, Interjoint coordination during pointing movements is disrupted in spastic hemiparesis, *Brain,* **119**(1996), 281–293.
15. M. Duarte and S. M. Freitas, Speed-accuracy trade-off in voluntary postural movements, *Motor Control,* **9**(2005), 180–196.
16. J. Förster, E. T. Higgins and A. T. Bianco, Speed/accuracy decisions in task performance: Built-in trade-off or separate strategic concerns? *Organ. Behav. Hum. Decis. Process,* **90**(2003), 148–164.
17. O. Missenard and L. Fernandez, Moving faster while preserving accuracy, *Neuroscience,* **197**(2011), 233–241.
18. S. L. Dejong, S. Y. Schaefer and C. E. Lang, Need for speed: better movement quality during faster task performance after stroke, *Neurorehabil. Neural Repair,* **26**(2012), 362–373.
19. R. C. Oldfield, The assessment and analysis of handedness: The Edinburgh inventory, *Neuropsychologia,* **9**(1971), 97–113.
20. G. T. Thielman, C. M. Dean and A.M. Gentile, Rehabilitation of reaching after stroke: Task-related training versus progressive resistive exercise, *Arch. Phys. Med. Rehabil.*, **85**(2004), 1613–1618.
21. S. Y. Schaefer, S. L. DeJong and K. M. Cherry, et al., Grip type and task goal modify reach-to-grasp performance in post-stroke hemiparesis, *Motor Control,* **16**(2012), 245–264.
22. P. M. van Vliet and M. R. Sheridan, Ability to adjust reach extent in the hemiplegic arm, *Physiotherapy,* **95**(2009), 176–184.
23. R. F. Molina, M. F. Rivas and D. H. T. M. Perez, et al., Movement analysis of upper extremity hemiparesis in patients with cerebrovascular disease: a pilot study, *Neurologia,* **27**(2012), 343–347.
24. L. B. Bagesteiro and R. L. Sainburg, Nondominant arm advantages in load compensation during rapid elbow joint movements, *J. Neurophysiol.*, **90**(2003), 1503–1513.
25. R. L. Sainburg, Convergent models of handedness and brain lateralization, *Front. Psychol.*, **5**(2014), 1092.

26. L. B. Bagesteiro and R. L. Sainburg, Handedness: Dominant arm advantages in control of limb dynamics, *J. Neurophysiol.*, **88**(2002), 2408–2421.
27. W. G. Yoo, Comparison of reaching velocity, upper trunk movement, and center of force movement between a dominant and nondominant hand reaching task, *J. Phys. Ther. Sci.*, **26**(2014), 1547–1548.
28. S. Barthélémy and P. Boulinguez, Manual asymmetries in the directional coding of reaching: further evidence for hemispatial effects and right hemisphere dominance for movement planning, *Exp. Brain Res.*, **147**(2002), 305–312.
29. K. C. Lin, C. Y. Wu and K. H. Lin, et al., Effects of task instructions and target location on reaching kinematics in people with and without cerebrovascular accident: a study of the less-affected limb, *Am. J. Occup. Ther.*, **62**(2008), 456–465.
30. P. H. McCrea and J. J. Eng, Consequences of increased neuromotor noise for reaching movements in persons with stroke, *Exp. Brain Res.*, **162**(2005), 70–77.
31. J. I. Todor and J. Cisneros, Accommodation to increased accuracy demands by the right and left hands, *J. Mot. Behav.*, **17**(1985), 355–372.
32. D. P. Carey, E. L. Hargreaves and M. A. Goodale, Reaching to ipsilateral or contralateral targets: within-hemisphere visuomotor processing cannot explain hemispatial differences in motor control, *Exp. Brain Res.*, **112**(1996), 496–504.
33. H. Carnahan, Manual asymmetries in response to rapid target movement, *Brain Cogn.*, **37**(1998), 237–253.
34. P. Boulinguez, V. Nougier and J. L. Velay, Manual asymmetries in reaching movement control. I: Study of right-handers, *Cortex*, **37**(2001), 101–122.
35. L. A. Knaut, S. K. Subramanian and B. J. McFadyen, et al., Kinematics of pointing movements made in a virtual versus a physical 3-dimensional environment in healthy and stroke subjects, *Arch. Phys. Med. Rehabil.*, **90**(2009), 793–802.
36. D. P. Carey and H. E. Otto-de, Hemispatial differences in visually guided aiming are neither hemispatial nor visual, *Neuropsychologia*,. **39**(2001), 885–894.
37. Y. Chen, H. Hu and C. Ma, et al., Stroke-related changes in the complexity of muscle activation during obstacle-crossing using fuzzy approximate entropy analysis, *Front. Neurol.*, **9**(2018), 131.
38. C. Ma, N. Chen and Y. Mao, et al., Alterations of muscle activation pattern in stroke survivors during obstacle crossing, *Front. Neurol.*, **8**(2017), 70.
39. Q. H. Huang, B. W. Wu and J. L. Lan, et al., Fully automatic three-dimensional ultrasound imaging based on conventional B-scan, *IEEE Trans. Biomed. Circuits Syst.*, **12**(2018), 426–436.
40. Q. H. Huang, Z. Z. Zeng and X. L. Li, 2.5-Dimensional extended field-of-view ultrasound, *IEEE Trans. Med. Imaging*, **37**(2018), 851–859.

AIMS Press

©2019 the Author(s), licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0)