Neuroscience Letters 683 (2018) 144–149

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Research article

Asymmetries in force matching are related to side of stroke in right-handed individuals

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ARTICLE INFO

Keywords:
Grasp
Force control
Stroke

ABSTRACT

Asymmetries in grasp force matching extend beyond quantifying a single measure of maximum grip strength and advance our application of side-specific treatment interventions. A cross sectional study design investigated grasp-force matching performance in right-handed individuals with a stroke and age-matched healthy controls. A visual representation of the 20% Maximum Voluntary Contraction (MVC) was matched in three conditions in the absence of visual feedback with the same (Ipsilateral Remembered – IR) or opposite hand (Concurrent – CC and Contralateral Remembered – CR). Greater overall relative error (RE) was found in contralateral compared to ipsilateral matching tasks. In the CR condition, post hoc analysis revealed significant differences between control and right hemisphere damage (RHD) group (95% CI [16.41–88.59]; $p < 0.01$) as well as left hemisphere damage (LHD) group and RHD (95% CI [23.4–95.09]; $p < 0.01$). Right hand matching relative error was 2.49 times larger in the RHD compared to the LHD group. Within the RHD group, matching errors were greater for the right than left hand in both contralateral conditions (95% CI [34.25–101.07]; $p < 0.001$).

Individuals with RHD showed greater asymmetries in contralateral matching tasks compared to LHD and controls. More specifically, the RHD group had the greatest difficulty matching tasks with their right (non-paretic) than left (paretic) hand. In order to elucidate this asymmetry in the clinic the use of complementary grasp measures may be considered.

1. Introduction

At least 48–88% of patients report upper impairments post stroke [1] and 50% of impairments persist for more than 3 months [1]. Changes in motor and sensory function predominantly affect the side of the body contralateral to the lesion, however deficits are present in both the affected and less affected limb [2,3]. Typically, the affected side is weaker and targeted for strength training more often than the less affected side. However, other factors such as pre-stroke grip strength and hand dominance may influence the course of recovery leading to a preferred use of one hand over the other. This may be problematic since both hands are used to perform at least 54% daily tasks [4] and persistent, preferential use of one hand may contribute to an eventual high reliance on others to care for them [5,6].

Following a stroke, muscle weakness is a key contributor to hand impairment [7,8] and greater losses occur in the hand than in the rest of the upper limb [9]. Upper extremity weakness correlates with declines in functional performance and at least 20lbs of grip strength, as measured with a hand dynamometer, are needed to perform most activities of daily living since recovery was based having enough strength to open common household containers [10]. Although maximum hand strength is used to quantify changes in strength [11] it is limited in its ability to capture important features associated with the control of grasp force such as generating steady forces to perform precise tasks [2,12–14]. Force deficits following a stroke may be represented by greater errors, higher variability, force irregularity and longer time lag between synchronizing muscle forces [3,13,33–37]. Individuals may demonstrate an inability to dynamically adapt to forces during a grasping task [15]. To complement a measure of maximum hand grasp, it has been suggested that quantifying the underlying components associated with the production and modulation of the control of grasp force may provide a better understanding of the motor components associated with poor

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https://doi.org/10.1016/j.neulet.2018.07.034
Received 16 April 2018; Received in revised form 17 July 2018; Accepted 21 July 2018

grasp function [16].

Although force deficits have been associated with the side of the body that had the stroke, it is not known how side of stroke contributes to the control of grasp force for each hand or when both hands work together. Indeed, hemispheric specialization [17–21] associated with reaching movements that differed for individuals with damage to the left or right hemisphere may also apply to tasks that require the control of grasp force. Further, side-specific differences in the relative distribution of forces between the hands while performing bimanual tasks differs [22] and, varies as a function of required target force, force generating capacity of the muscle, muscle effort and the availability of visual feedback [23,24].

Force matching tasks used in healthy young populations [25–27] showed that right and left hand matching ability varied as a function of differences between right and left hand grip strength and hand preference [41,42]. For right-handed participants, grasp force matching errors were greater when matching the reference force with the opposite than with the same hand in young [28,29] and older [30] adults. Contralateral matching showed right hand overshoots of left hand reference forces and left-hand undershoots of right hand reference forces that, further, were greater when the right hand was at least 5% stronger than the left hand. In contrast, right and left differences in hand strength and direction of matching errors (overshoots, undershoots) were not found in left-handed young participants [28].

The purpose of this study was to determine if right-handed individuals with an ischemic MCA stroke to the right (RHD) or left (LHD) hemisphere differed in their ability to match hand forces with their affected and less affected hand. It was hypothesized that 1) asymmetries in matching grasp forces would depend on side of stroke and 2) matching errors would be less for controls than individuals with a stroke. Previous studies investigating asymmetries focused on reach to grasp or reaching trajectories. This is the first study that compares the ability to match hand grasp forces independently of reach. This allows us to gain a better understanding of how grasp is incorporated into the performance of tasks and highlights the notion that grasp force control may be thought of independently of grasp strength.

2. Material and methods

2.1. Participants

Individualspost stroke were included if their stroke occurred more than one month or less than seven years from the date of testing, less than three times on the same brain side and if they had not received baclofen or Botox injections to reduce spasticity. Medical records/neurologist confirmed the presence of an ischemic, unilesional cortical/subcortical stroke which was confirmed by MRI data when available. Age-sex matched healthy controls reported no history of neurological problems. All participants scored above the inclusion criteria of 24/30 on the Mini-Mental State Examination (MMSE) and 44 or greater on the Fugl-Meyer UE motor score. Participants were recruited through the University Health Center, Detroit Medical Center Rehabilitation Institute of Michigan, Institute of Gerontology and local stroke support groups associated with Henry Ford Hospital. Each participant signed an approved Wayne State University, Human Investigation Committee informed consent form. Healthy controls were recruited from a previously established callback list in order to match age and sex with individuals who had a stroke.

2.2. Experimental procedures

2.2.1. Screening tools and assessments

Hand laterality was assessed using the 10-item Edinburgh Handedness Inventory (EHI). Individuals who suffered a stroke were asked to report the hand primarily used to perform a specific task twice (pre- stroke and post- stroke) and healthy controls completed the survey once. The Stroke Impact Scale (SIS) [31] was used to rate the level of difficulty associated with performing 59 items in 8 domains to include: strength, hand function, ADL/IADL, mobility, communication, emotion, memory and thinking and participation/role function. Hand strength (Item 1), ADL function (Item 5) and hand function (Item 7) are reported in the present study. The Fugl-Meyer (FM) Assessment of Physical Performance [32] was used to assess motor and sensory recovery post stroke.

Maximum grip strength measurements were taken with the Jaymar™ dynamometer using a standardized posture [33]. The average of two maximum voluntary contractions (MVC) was recorded. To avoid fatigue, MVC exertions alternated between hands with a 1-min rest break between exertions. A 5-min rest period was provided after taking the MVC measurements. A subgroup of participants was retested for MVC measures immediately following the experiment to ensure fatigue did not interfere with performance.

2.3. Experimental set-up

Participants were seated in a standardized posture in front of a computer monitor (For further details see previous work [28]). In brief, with elbows flexed at 120°, forearms fully pronated and wrists positioned between 25–30 deg of extension, participants grasped custom-designed horizontal cylindrical grasp devices embedded with strain

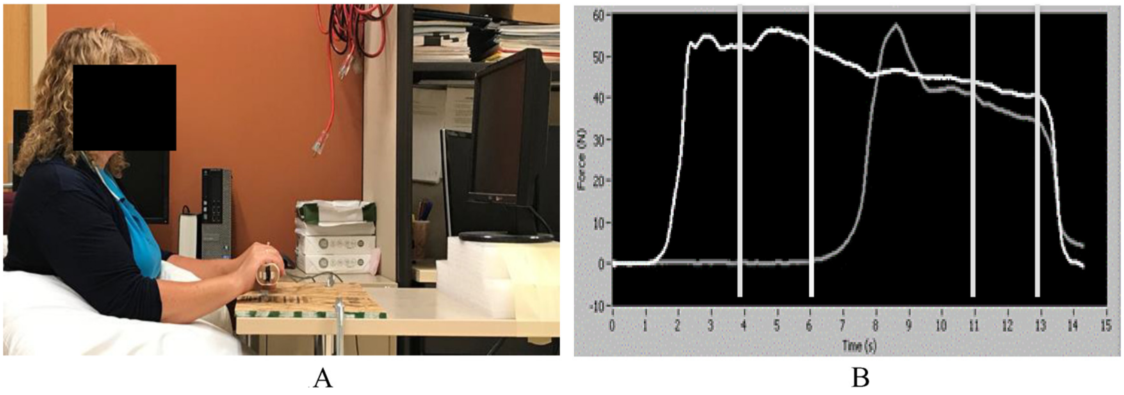
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Fig. 1. A. Standardized posture for testing. The strain gauges are equipped with semicircular wooden handles 4.0 cm in radius, 13 cm in length and were held horizontally by a coupling support fixed to the table. The device was placed in front of the participant and allowed for adequate finger clearance. A power grip pattern was used to position the hand around the device and fit to each individual's anthropometry. The computer monitor was placed 58.4 cm away from their eyes. B. The CC condition is represented here. Moving vertical cursors allowed the data analyst to place the cursors along the force profile whereby the most stable range of data points were collected. At 100 Hz frequency, then 200 data points were averaged to obtain the reference force (white) and matching (gray) force output.

Table 1
Mean (SD) of characteristics for controls and individuals with right hemisphere damage (RHD) and left hemisphere damage (LHD). Significant differences were found between controls and RHD groups for no. of comorbidities ($p = 0.002$) and controls and LHD groups ($p = 0.005$). The LHD group showed significantly difference between pre/post EHI scores ($p < 0.05$). No significant differences were found between the RHD and LHD groups for FM-UE motor/sensory and SIS scores. Significant differences in R and L grip strength was found in the RHD group only.

Group	Controls (n = 29)	RHD (n = 26)	LHD (n = 27)
Age mean (SD)	60.9(13.1)	60.2(11.1)	60.3(14.3)
MMSE mean (SD)	28.3(1.5)	28.2(2.2)	27.4(2.0)
No. Comorbidities	2.6 (1.6)	4.1(2.0)	3.9(1.6)
Years since stroke	na	3.8(2.6)	3.67(2.4)
EHI	0.92(0.1)	0.86(0.2)	0.89(0.2)
EHI post stroke	na	0.82(0.3)	0.58(0.5)
FM – UE motor	na	57.9(12.6)	58.3(9.2)
FM – UE sensory	na	10.3(2.8)	10.8(2.4)
Stroke Impact Scale	na		
Hand strength (1)	na	56.4(19.1)	53.6(18.0)
ADL function (5)	na	77.8(22.0)	78.7(18.4)
Hand function (7)	na	50.4(17.9)	65.2(28.2)
MVC right (kg)	30.9 (9.7)	31.0(13.4)	23.0(11.24)
MVC left (kg)	30.6(11.0)	19.4(10.4)	24.4(10.1)

gauges (See Fig. 1A). A 20% MVC was calculated to determine the reference force for the right and left hands. Visual feedback of the reference force was displayed on the computer monitor and available to the participants during practice and test trials. Visual feedback was not available during the match.

2.3.1. *Grasp force matching tasks*

Variations of this well-established paradigm have been commonly used [26,29]. In the Ipsilateral Remembered (IR) condition, memorized reference force information was transferred to the same hand/hemisphere system in order to produce a match in the same hand. In the Contralateral Concurrent (CC) condition, reference force information was transferred to the opposite hand/hemisphere system and both hands produced a force simultaneously. In the Contralateral Remembered (CR) condition, memorized reference force information was transferred to the opposite hand/hemisphere system in order to produce a match in the opposite hand. Each participant performed 2–3 practice trials to ensure they understood the instructions. After practice trials, the participants performed 3 trials for each condition (IR, CC, CR) and reference hand (R,L) combination for a total of 18 trials. A randomized block design was used to counterbalance side of stroke and reference hand for force matching tasks.

2.3.2. *Data acquisition and processing*

The analog signals from both transducers were digitized at 100 Hz and low-pass filtered (4th order Butterworth, zero phase lag, 6 Hz cutoff frequency) using customized software (LabVIEW, National Instruments). Reference and matching forces were computed by averaging the force signal over the most stable region (< 5% variation over a 2 s period). The average % target difference ($F_{ref} – F_{match}/F_{ref} \times 100$) between the reference and matching force constituted the RE (See Fig. 1B).

2.3.3. *Data analysis*

One-way analysis of variance ANOVAs, paired and independent t tests were used to test for within and between group differences for demographic data and clinical measures. To analyze the force matching data, we used the Shapiro-Wilk test to verify normal distribution of RE across conditions. A General Linear Model with repeated measures ANOVA was used to test for within subject factors hand (R, L) × condition (IR, CC, CR) and a between subjects factor for group (Control, RHD, LHD). Force matching relative error (RE) was reported as the mean (SE). Post hoc comparisons based on Bonferonni adjustments for multiple comparisons were used as needed. A secondary analysis was conducted to test for between group differences of absolute hand strength to force matching performance.

2.3.3.1. *Power analysis*

Estimates of effect size based on Cohen's *d* were calculated using t-tests and corresponding standard deviations from limited published data investigating some components of force control in stroke and older populations. Effect sizes for paired comparisons and 2-independent samples ranged from 0.63 to 0.75 with 10–18 participants per group. Previous data using a force matching paradigm [26,29] showed effect sizes between 0.45–0.76 with samples of 15 per group. Group differences (healthy, right side and left side stroke) rendered a sample of 25 participants per group for an effect size in the 0.75–0.80 range (Cohen's *d* indicating a large effect).

3. Results

3.1. *Participants*

Right-handed individuals (pre-stroke) with RHD, LHD, and age-sex matched controls completed clinical assessments and hand grasp matching tasks. Four individuals scored below the MMSE criteria and 5 individuals scored below the F-M UE motor score criteria and did not continue with the rest of the study. A total of control (n = 29), LHD (n = 26) and RHD (n = 26) individuals completed the study (See Table 1).

3.2. *Screening tools/clinical assessments*

Pre EHI and post EHI scores differed for the LHD group ($p < 0.05$) only. For the RHD group, right and left grip strength was significantly different ($p < 0.05$) only (See Table 1 for details). A subset of individuals showed no significant differences in pre/post MVCs performed with the left and right hand (See Table 2).

3.3. *Force matching relative error*

When the reference and corresponding matching forces were normalized to each hand's % MVC, the repeated measures ANOVA showed a significant main effect for group ($F(2,78) = 6.0$; $p < 0.01$) and a hand (right, left) × condition (CR, CC, IR) interaction ($F(2,78) = 11.5$ $p < 0.01$). In the CR condition, right hand matches were significantly different between the control and the RHD groups (95% CI [16.41–88.59]; $p < 0.01$) and LHD and RHD groups (95% CI [23.4–95.09]; $p < 0.01$) (See Fig. 2A). In the CC condition, right hand matches between the control and the RHD groups (95% CI [19.8–80.65]; $p < 0.01$); and between the LHD and RHD groups (95% CI [1.81–66.87]; $p < 0.05$) were significant. The LHD group and controls showed similar matching errors (95% CI [−38.91 to 7.11]; $p > 0.05$). LHD group differences for right (50.1 ± 6.4% MVC) and left (35.5 ± 3.9% MVC) hand matching were not significant in the CR condition (95% CI [−7.02 to 36.30]; $p > 0.05$) (See Fig. 2A). For the RHD group, right (97.1 ± 13.7% MVC) and left (37.0 ± 4.4% MVC)

Table 2
Mean (SD) for pre/post MVC right, MVC left for the control, RHD and LHD groups. No significant differences were found for pre/post MVC right, MVC left for any group.

Group	MVC Right		MVC Left	
	Pre	Post	Pre	Post
Controls (n = 10)	31.6(12.4)	30.9(12.7)	31.5(13.2)	30.2(12.1)
RHD (n = 10)	27.7(7.7)	27.0 (8.1)	19.5(8.3)	19.8(8.9)
LHD (n = 10)	25.6(12.3)	25.3(11.6)	20.1(5.7)	20.5(6.4)

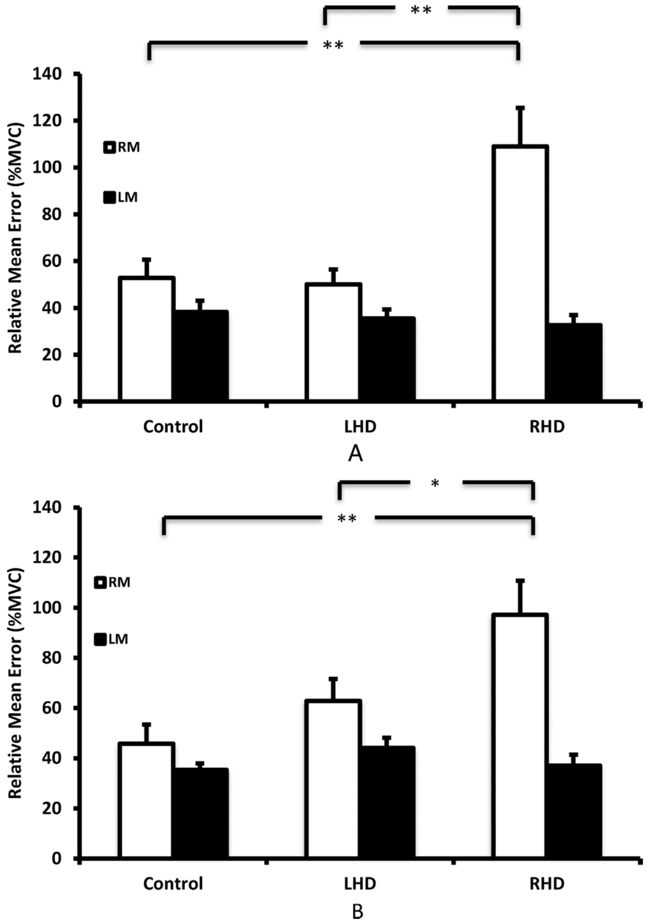

Fig. 2. A. Contralateral remembered matching. Mean (+1 SE) relative error (in % MVC) in the CR matching condition for right (*white bar*) and left (*solid bar*) match for the control, left hemisphere damage (LHD) group and right hemisphere damage (RHD) group. Significant differences were found between control (52.8 + 7.8% MVC) and RHD (109.0 + 16.4% MVC) group for right hand (**$p < 0.01$) matching and between the LHD (50.1 + 6.3% MVC) and RHD (109.0 + 16.4% MVC) groups for right hand (**$p < 0.01$) matching. B. Contralateral concurrent matching. Mean (+1 SE) relative error (in % MVC) in the CC matching condition for right (*white bar*) and left (*solid bar*) match for the control, LHD and RHD group. Significant differences were found between control (45.8 + 7.6% MVC) and RHD (97.1 + 13.7% MVC) groups (**$p < 0.01$) and LHD (62.7 + 8.84% MVC) and RHD (97.1 + 13.7% MVC) groups for right hand matching (*$p < 0.05$).

hand matches in the CC condition (95% CI [34.88–85.30]; $p < 0.001$); and right (109.0 ± 16.4% MVC) and left (41.6 ± 4.4% MVC) hand matches in the CR condition (95% CI [34.25–101.07]; $p < 0.001$) were significant. In the IR condition, there were no significant between or within group differences for right or left hand matches ($p > 0.05$).

4. Discussion

Individuals with a stroke showed greater errors than age-matched healthy controls. The purpose of this novel study was to elucidate asymmetries associated with grasp force matching in right-handed individuals with a right or left side stroke. Previous studies focused on affected limb regardless of preferred use and grasp and reach tasks. Unique to this study, is the ability to focus on the grasp component independent of reach and to consider the implications of sustaining a grasp that is independent of hand or grip strength. A simple grasp force-matching task revealed asymmetries that showed individuals with left hemisphere damage and who were right handed before their stroke performed better than those with right hemisphere damage and right hand function relatively preserved. Findings offer insight into recovery trajectories and examination specific to the side of stroke.

Previous studies have compared force deficits in healthy and stroke populations [2,33–35]. When performing unimanual and bimanual force production tasks, higher force variability [33–35] slower reaction time to produce a force [19] and longer time-lags between bimanual exertions [3] were found for stroke when compared to healthy controls. The production of force magnitude and variability between the paretic and non-paretic hands is asymmetric when compared to control groups [4–47]. Asymmetries associated with bimanual force tasks were associated with the magnitude of right and left hand strength differences found to persist regardless of the % MVC of the target force (5%, 25%, 50%) [23,29]. Lodha et al. showed that the affected paretic limb produced 60% and the less affected non-paretic limb produced 40% of the total force required to bimanual force production grasping task performed at three submaximal force levels. In comparison, when the control group performed the same task the distribution of forces between the hands relative to the target force was more symmetric. The distribution of forces by each hand remained consistent across force levels (5%, 25%, 50%) for both the control and stroke groups which lead the authors to conclude that the control mechanism that specifies force distribution strategy between the limbs at submaximal force levels remains intact post stroke [46,47].

Impaired force perception or sense of effort was attributed to changes in afferent peripheral information and leads to an overestimation of the magnitude of the force produced relative to the actual force [23]. Another study found that weights lifted by the weaker paretic limb relied on a sense of effort and an overestimation of force resulted from the increased motor command needed to overcome the reduced motor outflow of the paretic muscles. Participants overestimated the amount of force necessary to grasp objects precisely in both contralesional and ipsilesional hand [3,37].

4.1. Right and left hand use post stroke

Although the majority of studies report the results of paretic and non-paretic limb use without regard to hand dominance [34], there is evidence to suggest that premorbid hand dominance and side of stroke interact to modulate motor performance [38]. Thus, in the present study only right-handed, age-matched participants were recruited. For stroke participants, pre-EHI and post EHI data was collected to verify changes in hand use most evident for the LHD group (pre 0.84 and post 0.56 EHI scores). The shift in EHI score was a result of reporting that both hands were used to perform a task, whereas before the stroke only the right hand was used to perform a task. In contrast, those with RHD showed a 0.03 difference post stroke (pre 0.87 and post 0.84 EHI scores) which suggests individuals with RHD continue to favor their right non-paretic dominant hand and fail to incorporate their left paretic non-dominant hand into daily activities. Although having a stroke is a devastating condition, it appears that having a stroke on the right side of the body may contribute to a faster recovery, greater use of both extremities and less risk for the eventual decline of overall functional independence when compared to individuals who suffer a stroke on the left side of their body. These findings are similar to previous studies for reaching and spontaneous functional upper extremity use post stroke [38,39].

Further, healthy older controls who demonstrated superior function of daily tasks reportedly used both arms together about 60% of the time with less frequent use of the right or left arm alone [39]. Age- related changes associated with increased preferential use of both hands and corresponding neural activity [40] may be responsible for the similarities in performance of force matching tasks in the healthy control and LHD groups. It may be inferred that findings from our study showing similarities in force matching performance between the controls and LHD stroke participants are related to continued use of both hands to perform daily tasks. In contrast, those who suffered RHD stroke are less inclined to use both hands to perform a task since their right dominant, preferred limb was still intact.

4.2. Right and left hand strength post stroke

Typically, the affected side is weaker than the unaffected side. Bertrand et al. [23] calculated a global mean force ratio by averaging the mean of three maximum force values for the paretic/non-paretic side. Lodha et al. [33] suggested that asymmetries were unrelated to maximum grip strength differences. Left and right hand strength differences in the RHD group (38.7% difference between hands) were not proportional to RE asymmetries in the present study. Thus hand strength differences offer only a partial explanation as suggested in previous studies [23,29]. Further, a secondary analysis on RHD (n = 16) and LHD (n = 16) participants with similar absolute differences between right and left maximum grip strengths showed that greater right than left hand matching errors persisted in the CR ($p = 0.012$) and CC ($p = 0.017$) conditions for the RHD group with no asymmetries found in the LHD group.

4.3. Potential contribution of underlying mechanisms

Transcallosal communication effectively down regulates the damaged hemisphere and up regulates the non-damaged hemisphere [41,42]. Transcallosal inhibition from the primary motor cortex of the contralesional hemisphere to the ipsilesional hemisphere is accompanied by an under-utilization of the affected arm, and an inability to scale and maintain constant force levels. This imbalance from the stroke lesion increases the probability for hemisphere specific effects to emerge, compared to that in the less effected group. If an individual already had a dominant left hemisphere due to their right hand dominance, a lesion in the right hemisphere could lead to a severe imbalance between left and right transcallosal communication. Drawing from the literature regarding the contribution of changes in interhemispheric inhibition between the motor dominant and non-dominant hemispheres for reaching movements may have some applicability in the current study. During the performance of unilateral movements, transcallosal projections inhibit movement from the contralateral arm [43–46]. However, damage to the motor dominant left hemisphere may result in increased responsivity to disinhibition since there is differential inhibitory control prior to the stroke [41,42]. Individuals with a stroke in the left hemisphere may generate greater overflow when performing contralateral matching tasks resulting in less error regardless of matching hand.

4.3.1. Motor lateralization

Right hand dominant individuals utilize efferent copy and feed forward mechanisms differentially to grasp objects with their right and left hand [17,26,28]. In right-handed individuals the left hemisphere contributes largely to feed forward mechanisms such as the trajectory of the arm [46] used for aiming movement. In contrast, the right hemisphere contributes to limb position accuracy and is associated with feedback mechanisms [46]. However, this lateralization offers only a partial explanation as to why larger errors were seen in the RHD with contralateral matching tasks of the right hand.

Other potential contributions to asymmetries in force matching performance may be attributed to alterations in brain structures such as the supplementary motor area (SMA), the sensorimotor cortex, the cingulate motor cortex since they are recognized as being specifically involved in processing and executing movements that require bilateral coordination [47]. Neural crosstalk consisting of facilitation and interference effects when two limbs are performing a similar task (in this case, grasping devices in the contralateral conditions) may also contribute to the imbalance of transcallosal transfer of sensory and/or motor information. Recent imaging techniques investigating simultaneous movement of the two arms have shown bimanually sensitive neurons appear to be directionally specific. Some evidence suggests that the left hemisphere plays a dominant role in organization of mirror-symmetrical movements whereas the right hemisphere specializes in organization of non-mirror movements through inhibition via the corpus callosum. However, the contribution of changes in the SMA relative to force matching asymmetries was not within the scope of the current work and requires additional research.

4.4. Limitations

Due to the inherit nature of a cross-sectional study, findings here provide only a snapshot of a patients' lengthy recovery. The current study did not include left handed individuals. The force level tested was at 20% MVC to align with the amount of strength needed to perform daily tasks, however future studies may extend the range of % MVC tested.

4.5. Conclusions

Findings recognize the need to include tasks that involve the control of grasp force in addition to strength training. Relying on changes in hand strength alone neglect to take into consideration how grasp force information is used to transferred across the hemispheres and contributes to performing bimanual tasks.

Funding

This work was supported by The Blue Cross Blue Shield of Michigan Foundation Grant awarded to Diane E. Adamo. For Charlie Anderson – support was received from the Physical Therapy Founders Endowment Scholarship.

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