Published in final edited form as:

Neuropsychologia. 2009 November ; 47(13): 2953–2966. doi:10.1016/j.neuropsychologia.2009.06.025.

Hemispheric Specialization and Functional Impact of Ipsilesional Deficits in Movement Coordination and Accuracy

Sydney Y. Schaefer^{1,4}, Kathleen Y. Haaland^{5,6}, and Robert L. Sainburg^{1,2,3,4}

¹Department of Kinesiology, The Pennsylvania State University, University Park, PA

²Department of Neurology, The Pennsylvania State University, University Park, PA

³The Penn State Neuroscience Institute, The Pennsylvania State University, University Park, PA

⁴The Gerontology Center, The Pennsylvania State University, University Park, PA

⁵Research Service, New Mexico Veterans Affairs Healthcare System, University of New Mexico, Albuquerque, NM

⁶Departments of Psychiatry and Neurology, University of New Mexico, Albuquerque, NM

Abstract

Previous studies have demonstrated that following unilateral stroke, motor impairment occurs both contralateral, as well as ipsilateral, to the lesion. Although ipsilesional impairments can be functionally limiting, they can also provide important insight into the role of the ipsilateral hemisphere in controlling movement and the lateralization of specific motor control mechanisms, given that unilateral arm movements are thought to recruit processes in each hemisphere. The purpose of this study was to examine whether left and right hemisphere damage following stroke produces different ipsilesional deficits, and whether our *dynamic dominance* model of motor lateralization can predict such deficits. Specifically, the dynamic dominance model attributes control of multijoint dynamics to the left hemisphere, and control of steady-state position to the right hemisphere. Chronic stroke patients with either left or right hemisphere damage (LHD or RHD) used their ipsilesional arm, and the control subjects used either their left or right arm (LHC or RHC), to perform targeted reaching movements in different directions within the workspace ipsilateral to their reaching arm. We found that the LHD group showed deficits in controlling the arm's trajectory due to impaired multijoint coordination, but no deficits in achieving accurate final positions. In contrast, the RHD group showed deficits in final position accuracy but not in the ability to coordinate multiple joints during movement, thereby providing additional evidence for the hemisphere-specific nature of motor deficits. Furthermore, while both the LHD and RHD groups were functionally impaired to the same degree on the Jebsen Hand Function Test (JHFT), our results suggest that the underlying mechanisms for such impairment may be hemisphere-dependent.

Keywords

Lateralization; Motor control; Stroke

© 2009 Elsevier Ltd. All rights reserved.

Corresponding author: Dr. Robert L. Sainburg Department of Kinesiology Pennsylvania State University 29 Recreation Building University Park, PA 16802 Telephone: 814-865-7938 Fax: 814-865-7937 rls45@psu.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

INTRODUCTION

Contralateral hemiparesis, or weakness opposite to the damaged hemisphere, is the primary source of functional limitation in stroke patients, and has been characterized by spasticity (Bourbonnais, Vanden Noven, Carey, & Rymer, 1989; Given, Dewald, & Rymer, 1995; Levin, 1996; Schmit, Dhaher, Dewald, & Rymer, 1999) and poor joint coordination (Beer, Dewald, Dawson, & Rymer, 2004; Beer, Dewald, & Rymer, 2000; Dewald, Pope, Given, Buchanan, & Rymer, 1995). However, motor deficits are also present in the arm on the same side of, or *ipsilesional* to, the damaged hemisphere (Haaland & Harrington, 1996; Sunderland, 2000; Sunderland, Bowers, Sluman, Wilcock, & Ardron, 1999), which previously had been thought to be “unaffected.” Although ipsilesional motor deficits are not as severe as those in the contralesional arm, they can substantially impact functional performance of activities of daily living (Desrosiers, Bourbonnais, Bravo, Roy, & Guay, 1996; Lang, Wagner, Edwards, & Dromerick, 2007; Wetter, Poole, & Haaland, 2005). The impact of ipsilesional deficits can be magnified in many stroke survivors who must use the ipsilesional arm as their primary controller (Rinehart, Singleton, Adair, Sadek, & Haaland, 2009; Vega-Gonzalez & Granat, 2005).

Early studies reported that while left hemisphere damage impaired movement of the contralesional *and* ipsilesional arms, right hemisphere damage impaired only the contralesional arm (Harrington & Haaland, 1991; Kimura & Archibald, 1974; Semmes, 1968; Vaughan & Costa, 1962), thereby suggesting a “major” role of the left hemisphere in controlling movement (Liepmann, 1900). However, later studies revealed substantial motor deficits in the ipsilesional arm following both left and right lesions. Clinical assessments have reported similar degrees of ipsilesional motor impairment following left and right hemisphere damage (Desrosiers et al., 1996; Wetter et al., 2005; Yelnik et al., 1996), but kinematic analyses have suggested that motor deficits are hemisphere-dependent (Fisk & Goodale, 1988; Haaland, Prestopnik, Knight, & Lee, 2004; Schaefer, Haaland, & Sainburg, 2007; Smutok et al., 1989). While movements of the ipsilesional arm tend to be slower and less “coordinated” following left but not right hemisphere damage (Hermsdorfer, Laimgruber, Kerkhoff, Mai, & Goldenberg, 1999; Levin, 1996; Sugarman, Avni, Nathan, Weisel-Eichler, & Tiran, 2002), final position accuracy tends to be reduced following right but not left hemisphere damage (Darling, Bartelt, Pizzimenti, & Rizzo, 2007; Hermsdorfer, Blankenfeld, & Goldenberg, 2003). It has been hypothesized that such differences may reflect hemispheric specialization of different aspect of movement control (Haaland & Harrington, 1989a, 1989b; Haaland et al., 2004; Winstein & Pohl, 1995).

We have recently provided evidence that hemisphere-dependent differences in motor control appear to reflect lateralization of motor function, based on a model of motor lateralization that describes a dominant hemisphere/limb system that is specialized for coordination of limb and task dynamics, and a nondominant system that is specialized for achieving static (steady-state) positions (Sainburg, 2002, 2005). In fact, recent studies have suggested a more general specialization of the nondominant hemisphere for stabilizing external loads (Duff & Sainburg, 2007; Schabowsky, Hidler, & Lum, 2007). Our “dynamic dominance” hypothesis emerged from studies in young healthy subjects that showed dominant arm advantages for coordinating intersegmental dynamics and adapting to altered inertial conditions, and nondominant arm advantages for achieving stable final positions, even in the presence of unexpected perturbations (Bagesteiro & Sainburg, 2002, 2003; Duff & Sainburg, 2007; Sainburg & Kalakanis, 2000; Sainburg & Wang, 2002). We also examined interlimb differences during single-joint movement (Sainburg & Schaefer, 2004), and found that the dominant and nondominant arms independently varied the amplitude and duration of initial torque in order to extend the elbow across a range of angles.

In general, our model of motor lateralization is a bihemispheric model of motor control, in which each hemisphere contributes to unilateral movement planning and control of each arm. Early research in primates clearly showed that the spinal projections from cortical and brainstem regions are primarily contralateral for distal limb musculature that is associated with reaching and grasping behaviors (Brinkman & Kuypers, 1972; Kuypers, 1964; Kuypers & Brinkman, 1970; Phillips, 1969); however, more recent electrophysiological and functional imaging findings have revealed substantial cortical activation in the ipsilateral hemisphere during unilateral arm movement (Donchin et al., 2002; Kawashima et al., 1993; Kim et al., 1993; Li, Yetkin, Cox, & Haughton, 1996; Singh et al., 1998; Tanji, Okano, & Sato, 1988). These findings have led some to posit that motor planning and control recruits bihemispheric networks, via callosal projections through which interhemispheric inhibition or excitation may occur (Bloom & Hynd, 2005; Geffen, Jones, & Geffen, 1994; Milner & Kolb, 1985; Preilowski, 1972). In chronic stroke patients, however, cortico-cortical connections may be reduced, with greater functional connectivity within the intact hemisphere (Gerloff, Bushara, Sailer, Wassermann, Chen, Matsuoka, Waldvogel, Wittenberg, Ishii, Cohen, & Hallett, 2006). Given that our model of motor lateralization proposes that the contribution of each hemisphere to the planning and control of movement has become specialized, we predict that even in chronic stages of stroke, unilateral lesions in the primary motor system should disrupt the contributions of that hemisphere to ipsilesional arm control. We hypothesize that left hemisphere damage will disrupt control of intersegmental coordination, and right hemisphere damage will disrupt control of limb position.

In an earlier study of single-joint arm movements in left- and right-hemisphere-damaged stroke patients (Schaefer et al., 2007), we found that patients with left hemisphere damage did not scale initial torque amplitude with distance but instead scaled torque duration, a strategy that we had previously attributed to right-hemisphere-specific mechanisms for final position control. In contrast, patients with right hemisphere damage scaled initial torque amplitude, but not duration, with distance, which resulted in larger errors in final position. We hypothesized that these interlimb differences in torque strategy corresponded to interhemispheric differences in control. However, this relationship remained largely speculative because we did not directly test whether differences in performance of single joint movements correspond to the lateralization of control mechanisms proposed by our model, which have been based on findings from multijoint studies in healthy young adults. In addition, we were unable to associate our findings in single-joint movements with functional performance of the ipsilesional arm. Therefore, the purpose of this study was to investigate multijoint coordination in the ipsilesional arm, and to assess how our findings relate to a common clinical measure of functional performance. We predicted that the ability to effectively coordinate the elbow and shoulder while reaching across different directions would be impaired following left hemisphere damage. We also predicted that the ability to achieve accurate final positions would be impaired following right hemisphere damage, based on our model of lateralization. In addition, we predicted that such impairment might be related to functional deficits.

METHODS

Participants

Fourteen right-handed hemiparetic stroke patients and 22 right-handed healthy control subjects were examined after obtaining approval from the Human Research and Review Committee of the University of New Mexico School of Medicine and the New Mexico Veterans Affairs Healthcare System, and informed consent from each participant, according to the Declaration of Helsinki. All subjects were screened and excluded based on history of 1) substance abuse and/or psychiatric diagnosis, 2) non-stroke neurological diseases for the stroke patients and all neurological diagnoses for the control subjects, and 3) peripheral movement restrictions, such

as neuropathy or orthopedic disorders. Seven stroke patients had left hemisphere damage (LHD), and 7 patients had right hemisphere damage (RHD). All stroke patients completed the experiment with their ipsilesional arm. All stroke patients were hemiparetic in the contralesional arm, as defined by a contralesional grip strength 1.5 standard deviations below normal and at least 1.5 standard deviations less than ipsilesional grip strength using a hand dynamometer. Additional measures of hemiparesis (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975), language comprehension (Kertesz, 1982), and limb apraxia (Haaland & Flaherty, 1984) were also used. Hemispatial neglect was evaluated with a modified line cancellation task (Albert, 1973). Patients with two or more errors (out of 21 possible) in the contralesional left or right hemispace were classified as having visual neglect, based on the fact that none of the control subjects made more than one error in either hemispace. Twenty-two age- and education-matched healthy control subjects completed the experiment with their left arm [LHC: $n = 11$; males = 8, females = 3; age (mean $\pm$ SD) = 62.6 ± 7.6 yrs] or right arm [RHC: $n = 11$; male = 10, female = 1; age (mean $\pm$ SD) = 61.6 ± 8.6 yrs].

MRIs (Phillips Edge 1.5 tesla scanner) were obtained in stroke patients with slice thickness of 5 mm and a slice gap of 1 mm. Due to medical contraindications for MRI (e.g., cardiac pacemakers), four patients (1 LHD and 3 RHD) had CT scans (Phillips PQ 6000 scanner) with slice thickness of 8 mm and no gaps between slices. A board-certified neurologist, who was blinded to the behavioral characteristics of the patients, outlined the area of damage for each patient on 11 standardized horizontal sections derived from the DeArmond atlas (DeArmond, Fusco, & Dewey, 1989) using T1 weighted MRI images for anatomical detail and T2 weighted images to specify borders of the damaged tissue (Fig. 1). These tracings were retraced on a digitizing tablet for input into a computer program that used an algorithm to calculate lesion volume and location within each hemisphere (Frey, Woods, Knight, Scabini, & Clayworth, 1987).

Experimental setup

Figure 2A illustrates the experimental setup. Participants sat facing a projection screen with either their left or right arm supported over a horizontal surface by an air-jet system to reduce the effects of friction and gravity. The arm was positioned just below shoulder height. The start circle, a target, and a cursor that represented finger position were projected on a horizontal back-projection screen positioned above the arm, with a horizontal mirror positioned below this screen. The mirror reflected the visual display, such that the projection appeared in the same horizontal plane as the fingertip. It is important to note that the virtual reality display was designed and calibrated to ensure that the projection was veridical (i.e. 1 centimeter leftward arm movements corresponded to 1 centimeter leftward cursor movement in the same plane). Subjects performed reaching movements below the mirror, without vision of the arm. The displayed cursor was the only visual feedback available to the subjects during the experiment.

All joints distal to the elbow were immobilized using an adjustable brace. Position and orientation of the segments proximal and distal to the elbow joint were sampled using a Flock of Birds (FoB) ® (Ascension-Technology) magnetic six-degree-of-freedom (6-DOF) movement recording system. A single sensor was attached to the upper arm segment via an adjustable plastic cuff, while another sensor was fixed to the air sled where the forearm was fitted. The sensors were positioned approximately at the center of each arm segment. The positions of the following three bony landmarks were digitized using a stylus that was rigidly attached to a FoB sensor: 1) index finger tip; 2) the lateral epicondyle of the humerus; 3) the acromion, directly posterior to the acromio-clavicular joint. These positions were relative to the sensors attached to each arm segment, thereby remaining constant throughout the experimental session. Our custom software used the FoB sensor data to compute the three-dimensional (3D) position of the index finger tip. Because the table surface defined our X-Y

plane, perpendicular axis displacement was constant; thus, we used the recorded X-Y coordinates of the fingertip to project a cursor onto the screen. Screen redrawing occurred fast enough to maintain the cursor centered on the fingertip throughout the sampled arm movements. Digital data were collected at 103 Hz using a Macintosh computer, which controlled the sensors through separated serial ports, and stored on disk for further analysis. Custom computer algorithms for experiment control and data analysis were written in REAL BASIC™ (REAL Software, Inc.), C and IgorPro™ (Wavemetric, Inc.).

Experimental task

All three targets were 2.5 cm in diameter, and were projected in the ipsilesional hemispace at a distance of 16 cm from the start position. The targets were oriented 40° clockwise, 0°, or 40° counter-clockwise from the start position (Fig. 2B); thus, subjects were instructed to reach their left or right arms to a *lateral* (away from midline), *center*, and *medial* (toward midline) target (Fig. 2C). These directions were selected in order to systematically vary the effective inertial load at the hand, and subsequently the dynamic requirements, between targets (Bagesteiro & Sainburg, 2002; Hogan, 1985; Sainburg & Kalakanis, 2000). The cursor, which corresponded to the real-time position of the index fingertip, and the start circle were displayed on the screen prior to each trial. The target did not appear until after the subjects had held the cursor within the starting circle (for 200 milliseconds) to trigger the audiovisual 'go' signal; the target for that trial then appeared. They were instructed to move their finger (cursor) to "the center of the target and stop, using a single, uncorrected motion." Feedback regarding the fingertip position (cursor) was given to allow subjects to position the hand in the start circle, and was then removed at the 'go' signal. No visual feedback of the hand was given during the movement. Although explicit knowledge of results was not provided at the end of the movement, subjects received a numerical score at the end of each trial to maintain motivation, based on the location of the index finger relative to the target at movement end. More specifically, final position errors of less than 1.25 cm from the center of the target (i.e. within the target circle) were awarded 10 points, while errors between 1.25 cm and 2.5 cm were awarded 3 points, and errors between 2.5 cm and 3.75 cm were awarded 1 point. The purpose of awarding points to each trial was merely to motivate our subjects; these points were not analyzed as dependent variables, and all trials were recorded and saved. Following the display of the numerical score after each trial, the cursor was redisplayed for accurate positioning of the fingertip back at the start circle for the next trial. The three targets were presented in a pseudorandom order over a session of 99 total trials, such that no single target was presented consecutively.

Kinematic Data

The 3D position of the index finger, elbow point, and shoulder point were calculated from sensor position and orientation data. Then, joint angles were calculated from these data. All kinematic data were low-pass filtered at 8 Hz (3rd order, dual-pass Butterworth), and differentiated to yield tangential velocity and acceleration values. Movement start was determined by identifying the time of peak velocity and searching backward in time for the first minimum in velocity (acceleration = 0) below 6% of peak tangential velocity. Movement end was similarly determined by searching forward in time from peak velocity to find the first minimum in velocity below 6% of peak tangential velocity, thereby excluding any small, corrective submovements.

Inverse dynamics

The arm was modeled as a 2-segment chain, with the proximal end (shoulder point) free to move in the horizontal plane. Using inverse dynamic analysis, values for muscle torque and interaction torque were calculated for each joint (elbow and shoulder). The sum of muscle and interaction torques (i.e. net torque) is directly proportional to joint acceleration and is inversely

proportional to limb inertia (Sainburg, Ghez, & Kalakanis, 1999). Joint muscle torque represents the rotational effect of muscle forces acting on the segment, but does not directly serve as a substitute for the neural activity within the muscles acting at that joint. Muscle torques may reflect, but cannot distinguish between, individual muscle forces that may counter each other during co-contraction. Muscle joint torques may include passive components of movement, such as the effect of soft tissue deformation. Nevertheless, we used joint muscle torque as a measure of net output of the neuromuscular system (Wadman, Denier van der Gon, & Derksen, 1980).

The equations below detail how the three torque components were computed and analyzed for the elbow and shoulder joints. The inertia and mass of the forearm support are 0.0247 kgm² and 0.58 kg, respectively. Limb segment inertia, center of mass, and mass were computed from regression equations using subjects' body mass and measured limb segment lengths (Winter, 1990).

Elbow joint torques:

$$\begin{aligned} T_{e_M} &= T_{e_N} - T_{e_1} \\ T_{e_N} &= (I_e + m_e r_e^2) \ddot{\theta}_e \\ T_{e_1} &= m_e r_e \sin(\theta_e + \theta_s) \ddot{x} - m_e r_e \cos(\theta_e + \theta_s) \ddot{y} - l_s m_e r_e \sin(\theta_e) \dot{\theta}_s^2 - (I_e + m_e r_e [r_e + l_s \cos(\theta_e)]) \ddot{\theta}_s \end{aligned}$$

Shoulder joint torques:

$$\begin{aligned} T_{s_M} &= T_{s_N} - T_{s_1} + T_{e_M} \\ T_{s_N} &= (l_s + m_s r_s^2 + m_e l_s^2 + m_e l_s r_e \cos(\theta_e)) \ddot{\theta}_s \\ T_{s_1} &= (m_s r_s \sin(\theta_s) + m_e l_s \sin(\theta_s)) \ddot{x} - (m_s r_s \cos(\theta_s) + m_e l_s \cos(\theta_s)) \ddot{y} \\ &\quad - \left(m_e r_e (l_e \cos(\theta_e) \ddot{\theta}_e + l_s \sin(\theta_e) \dot{\theta}_e^2 + 2l_s \sin(\theta_e) \dot{\theta}_s \dot{\theta}_e + l_s \sin(\theta_e) \dot{\theta}_s^2) \right) \end{aligned}$$

where m is segment mass, r is distance from proximal joint to center of mass, l is segment length, I is segment inertia, θ_s is shoulder angle, θ_e is elbow angle, x is shoulder position along x direction, y is shoulder position along y direction, T_{e_I} is elbow interaction torque, T_{e_M} is elbow muscle torque, T_{e_N} is elbow net torque, T_{s_I} is shoulder interaction torque, T_{s_M} is shoulder muscle torque, and T_{s_N} is shoulder net torque. Subscript e denotes lower arm segment, and s denotes upper arm segment. Derivations of joint torques have been described previously (Bagesteiro & Sainburg, 2002).

Dependent measures

The following measures were calculated for each trial: Reaction time, movement time, absolute and variable error, peak tangential and joint velocity, handpath curvature, initial movement direction, and initial joint muscle torque. Reaction time was defined as the time elapsed from target appearance to movement start. Movement time was defined as the elapsed time from movement start to movement end. Absolute error, a measure of accuracy, was calculated as the absolute value of the distance from the index fingertip at movement end to the center of the target. Variable error, a measure of consistency, was calculated as the distance from the index fingertip at movement end to the mean final position for each target. We also computed variable error during movement, calculated as the distance from the index fingertip's location at peak tangential velocity to its mean location at peak velocity for each target. Peak tangential velocity was defined as the absolute maximum tangential velocity, while peak joint velocities were defined as the absolute maximum angular velocities produced at the elbow and shoulder.

Handpath curvature was calculated as the minor axis divided by the major axis of the hand path. The major axis was defined as the largest distance between any two points in the handpath, while the minor axis was defined as the largest distance, perpendicular to the major (Fig. 3) (Bagesteiro & Sainburg, 2002; Sainburg, Poizner, & Ghez, 1993). Initial movement direction was measured in a right-arm coordinate system, relative to the line connecting the start location and the target location. Initial movement direction was calculated as the angular deviation between this "target line" and the line from the starting location of the hand to the position of the hand at peak tangential acceleration (~ 100 ms). Positive values indicate hand paths that were directed lateral (clockwise: CW) to the target line (in a right-arm coordinate system), whereas negative values indicate hand paths that were directed medial (counter-clockwise: CCW) to the target line. This angle describes the difference between the target direction and the actual movement direction during the earliest phase of motion. Initial peak torque was calculated as the maximal flexor (positive) or extensor (negative) muscle and interaction torque produced at the shoulder and elbow from time of movement start to the time of peak tangential acceleration.

Because this study was designed to test whether our model of motor lateralization can predict functional deficits in the ipsilesional arm of stroke patients, we included subjects' performance on the Jebsen Hand Function Test when using their ipsilesional hand to assess its level of functional ability. The Jebsen Hand Function Test (JHFT) is a widely-used objective test of hand function during simulated activities of daily living that includes a variety of timed motor activities (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969). Although this clinical test was designed to assess *hand* function, many of the tasks require arm coordination to ensure effective execution, such as checker-stacking and simulated feeding; thus, one's JHFT performance may reflect one's ability to control movements of the entire upper extremity. Our control subjects completed the JHFT using the same arm that was used to complete the experimental task.

Statistical Analysis

Because our task was designed to examine how the presence and side of unilateral brain damage would affect motor performance across varying dynamic requirements between targets (Bagesteiro & Sainburg, 2002; Hogan, 1985; Sainburg & Kalakanis, 2000), the means of individual dependent measures were analyzed using 3-way mixed model analysis of variance (ANOVA), with arm (left = L or right = R) and lesion status (healthy control = HC or hemisphere damage = HD) as between-subject factors, and target (lateral, center, and medial) as the within-subject factor. Based upon our hypothesis, we predicted significant 3-way interactions for trajectory- and position-based parameters, which should reflect changes in joint coordination, speed, and final accuracy as a function of target and hemisphere of damage. Standard deviation (SD) and coefficient of variation (CV) were used to quantify within-subject variability of dependent measures. When warranted by significant interaction, post-hoc analysis was performed using Tukey HSD. We also correlated movement variables with Jebsen performance using linear regression, reporting Pearson's r (two-tailed significance) as the relevant measure.

RESULTS

Subject characteristics

Table 1 summarizes the characteristics of each patient in each group. Age ($F_{3,32} = 0.36$; $p = .80$) and education ($F_{3,32} = 0.81$; $p = .50$) were similar across all groups. Student's t -test revealed that the LHD and RHD groups did not significantly differ in number of years post stroke ($p = .62$), limb apraxia ($p = .75$), or degree of hemiparesis based on contralesional grip strength ($p = .09$) or on the Upper-extremity motor subscore of the Fugl-Meyer Motor Assessment (p

= .10). The LHD group had significantly lower language comprehension scores than the RHD group on the Western Aphasia Battery ($p < .05$). The LHD group also had significantly higher scores than the RHD group on the Jebsen Hand Function test ($p < .05$). Mild contralesional visual neglect was present in only two LHD patients and one LHD patient (i.e. ~ 10% error on line cancellation test).

Total lesion volume was not significantly different between the LHD and RHD groups ($p = .18$), but there was within-group variability of lesion location and size (see Fig. 1). The extent of damage for each patient is described also in Table 1. All patients had strokes in the distribution of the middle cerebral artery, with one RHD patient having additional damage in the anterior cerebral artery distribution. All patients had damage in at least one region of the primary motor system (Brodmann Areas 4, 6, 3, 1, 2 and/or internal capsule), as confirmed by positive assessment of contralesional hemiparesis. More specifically, all RHD patients and five of seven LHD patients had damage in motor and premotor cortex. In addition, damage to the putamen was quite common, especially in the LHD group. Despite within-group variability of lesion location and/or size, it is unlikely that the crossed interactions between group and side of lesion could be fully explained by group differences in intrahemispheric lesion characteristics. We observed qualitative differences in deficits between the LHD and RHD groups, and it is unlikely that variations in the size of somatomotor cortex, dorsolateral prefrontal cortex, or putamen lesions would result in selective impairment in adaptation of either trajectory or position independently.

Task performance

Figure 4 shows mean ($\pm$ SE) reaction time, movement time, peak velocity, and absolute error across subjects for each target in each group. Consistent with these plots, our ANOVA revealed that the right hemisphere damage (RHD) group had longer reaction times that varied with target direction, compared to the left and right healthy control (LHC, RHC) groups and the left hemisphere damage (LHD) group. This significant interaction between arm (L or R), lesion status (HC or HD), and target (lateral, center, and medial) for reaction time is shown in Figure 4A ($F_{2,32} = 4.75$; $p < .05$). Post-hoc analysis revealed that regardless of target direction, reaction times were longer for the RHD group than for all other groups by approximately 70-100 ms ($p < .05$). Moreover, there was no difference in reaction time between the LHD and LHC groups ($p = .91$).

Although there were no significant interactions between factors for movement time ($F_{2,32} = 0.69$; $p = .50$), there was a significant main effect of lesion status ($F_{1,32} = 13.84$; $p < .001$), with longer times for both HD groups relative to the HC groups (Fig. 4B). There was also a main effect of target on movement time ($F_{2,32} = 22.48$; $p < .0001$), such that the duration of movements in the medial direction were significantly longer than in the center or lateral directions, despite having the same target distance (16 cm). This is consistent with the work of Gordon et al. (Gordon, Ghilardi, Cooper, & Ghez, 1994; Gordon, Ghilardi, & Ghez, 1994), which showed that while reaching across multiple directions, movement times are longer in directions associated with higher limb inertia (i.e. along the long axis of the forearm), an effect that appears to compensate for inertial dependent differences in limb acceleration.

Consistent with our previous study of single joint movements (Schaefer et al., 2007), the RHD group showed larger absolute errors in final position relative to control subjects, while the LHD group was as accurate as the LHC group (Fig. 4C). Our ANOVA indicated a significant interaction between arm and lesion status, but not target, for absolute error ($F_{1,32} = 8.70$; $p < .01$), with errors of approximately 4 cm for the RHD group, and only 2 cm for all other groups. Post-hoc analysis revealed that while the RHD group had significantly larger errors than the RHC group ($p < .05$), the LHD group was not significantly different from the LHC group in terms of final position accuracy ($p = .32$). These findings support a specialized role of the right

hemisphere in achieving accurate final position, and appear to be consistent with previous data suggesting a right hemisphere specialization for positional control (Duff & Sainburg, 2007; Schabowsky et al., 2007).

Previous studies have shown significant reductions in movement speed in patients with left hemisphere damage when using the ipsilesional arm (Fisk & Goodale, 1988; Haaland & Harrington, 1994; Haaland et al., 2004; Winstein & Pohl, 1995; Yelnik et al., 1996). Consistent with these earlier findings, only our LHD group had lower peak velocities relative to their control group (Fig. 4D). Our ANOVA revealed a significant interaction between arm and lesion status, but not target, for peak velocity ($F_{1,32} = 5.55$; $p < .05$). Post-hoc analysis indicated that the LHC, RHC, and RHD groups moved at comparable speeds that were significantly greater than those of the LHD group, regardless of target ($p < .05$). It should be stressed that because the RHD group produced velocities that were comparable to their control group, the larger errors in final position of the RHD group did not appear to be associated with differences in movement speed, i.e. trade-off between speed and accuracy. Likewise, although the LHD group moved considerably slower with longer movement times than their control group, they were not more accurate.

Handpath curvature

Figure 5A shows typical handpaths of a representative subject from each group. The handpaths of the left-hemisphere-damaged (LHD) patient were very curved, with the amount of curvature increasing across directions. These effects were consistent across subjects, as shown in the graphs of average ($\pm$ SE) handpath curvature (Fig. 5B). The handpaths of the LHD group were significantly more curved than those of the control groups and the RHD group, and the change in curvature with direction was most pronounced in the LHD group. Our ANOVA confirmed these effects by revealing a significant interaction between arm, lesion status, and target for handpath curvature ($F_{2,32} = 6.01$; $p < .01$). Post-hoc analysis revealed that the handpaths of the LHD group to the medial target were the most curved relative to all other subject groups and directions ($p < .05$). Though smaller in amplitude, similar effects of movement direction on trajectory curvature have been shown to depend on the amplitude of intersegmental dynamics during reaching movements in healthy subjects (Gribble & Ostry, 1999; Sainburg, Ghilardi, Poizner, & Ghez, 1995; Smith & Zernicke, 1987).

Inverse dynamic analysis

Figure 6A shows the handpaths of two movements to the medial target for an LHD patient and an RHD patient. These hand paths represent the range of initial movement directions for each subject, corresponding to the trials with the most positive (CW) and most negative (CCW) initial movement direction for each patient, with respect to a right-hand coordinate system. As shown, the range of initial movement direction was much larger for the LHD patient than for the RHD patient, indicating a much larger variation in initial direction across trials. This was consistent for all LHD patients; to quantify this, we computed the standard deviation (SD) of initial movement direction to each target for each subject, and then compared average SD across groups. Our ANOVA showed a significant interaction between arm, lesion status, and target for the SD of initial movement direction ($F_{2,32} = 3.84$; $p < .05$), with post-hoc analysis revealing that the LHD group had significantly larger variability than the other groups when reaching to the center and medial targets ($p < .05$). The mean SDs of initial movement direction when reaching to the medial target are shown in Figure 6B for all groups. However, when reaching to the lateral target (not shown), the variability in initial movement direction for the LHD group was not significantly different from all other groups ($p = .12$). In this direction, the mass of the upper arm contributes little to total arm inertia, resulting in smaller amplitude intersegmental interactions that can influence limb acceleration.

Figure 6C shows the joint torque profiles corresponding to the first 100 milliseconds of the handpaths in Figure 6A. Positive values indicate flexor torque; negative values indicate extensor torque. While muscle torques at the shoulder (Fig. 6C, top), and interaction torques at the elbow (Fig. 6C, middle), were fairly similar between the two patients, the muscle torques at the elbow (Fig. 6C, bottom) were quite different. The RHD patient initiated both movements with small amplitude flexor elbow muscle torques, while the LHD patient initiated one movement with a large amplitude flexor muscle torque, yet initiated the other movement with *extensor* muscle torque, resulting in a large range of initial movement directions (see Fig. 6A). These differences in within-subject variability (as measured as coefficient of variation, CV, within subject) of initial peak elbow muscle torque were consistent across groups. Although our ANOVA revealed a significant main effect of lesion status on initial peak shoulder muscle torque variability ($F_{1,32} = 8.67$; $p < .01$), with post-hoc analysis indicating greater variability in the HD group ($p < .05$), this effect was similar for the LHD and RHD groups, as evidenced by no significant interaction effects. There were also no significant main or interaction effects for elbow interaction torque. However, there was a significant interaction between arm, lesion status, and direction for the CV of initial peak elbow muscle torque ($F_{2,32} = 3.59$; $p < .05$), with post-hoc analysis indicating that the variability in initial torque was significantly larger for the LHD group relative to the other groups only when reaching to the medial target. The mean CVs of initial peak shoulder muscle, elbow interaction, and elbow muscle torque when reaching to the medial target are shown in Figure 6D for all groups. Thus, under conditions in which substantial interjoint interactions may influence limb acceleration (i.e. reaching to the medial target), the LHD group showed more variability in *where* movements were initiated in the workspace (initial movement direction), and *how* movements were initiated by elbow musculature (initial muscle torque).

Double dissociation between final position and initial trajectory with hemisphere damage

As shown earlier in Figure 6, the RHD patient generated consistently small amplitude muscle torque at the elbow and made consistently straight handpaths to a given target; however, this patient showed large variation in final position relative to each target. Figure 7A demonstrates this dissociation, showing the location of the hand during movement at peak velocity (+) and at the end of movement (•) across all trials for an LHD patient and RHD patient. The considerable overlap between the hand's location at peak velocity for the LHD patient, as well as the overlapping density ellipses (CI = 95%), emphasize how these movements were not initiated in specific directions relative to the target location. In contrast, the narrow and separated density ellipses corresponding to the hand's location at peak velocity for the RHD patient reflect well-aimed reaches in specific movement directions. However, these variations in movement initiation did not correspond to variability at movement end. The LHD patient effectively corrected back to the target, resulting in small distributions of hand location at movement end, whereas the RHD patient's final hand locations were more scattered. When we computed the within-subject *ratio* of variable error of each subject's hand position during movement (at peak velocity) relative to the end of movement, the effects of lesion side were more apparent. Figure 7B shows the ratio of variable error for each group; values > 1 indicate more variable error during movement (at peak velocity) than at the end of movement, while values < 1 indicate more variable error at the end of movement than during movement. Our ANOVA revealed a significant interaction of arm and lesion status on the ratio of variable error ($F_{1,32} = 8.36$; $p < .01$), and post-hoc analysis determined that the RHD group had significantly smaller ratios than the all other groups ($p < .05$). The crossed interaction between side of lesion and how variable movements were initiated relative to where they ended not only illustrates the distinct control of trajectory and position, but also provides evidence for lateralization of the control mechanisms underlying these two processes.

Hemisphere-specific predictors of functional impairment

Figure 8 (top) shows that the amount of handpath curvature strongly predicted ipsilesional performance of simulated activities of daily living (Jebsen Hand Function Test) *only* in the LHD group, despite having a similar range of scores (54-131 seconds) as compared to the RHD group (55-137 seconds). In other words, LHD patients with larger handpath curvatures took longer to complete the JHFT, suggesting that deficits in the ability to coordinate muscle actions during goal-directed movement following left, but not right, hemisphere damage may be an underlying cause of less efficient performance in functional tests involving multijoint movements.

These findings do *not*, however, explain why the RHD group was slower than control subjects in the JHFT test when using their “unaffected” dominant right hand. These patients did not have lower peak velocities or demonstrate abnormal joint coordination, given their ability to systematically produce straight handpaths over a range of movement directions. Because the RHD group took longer to initiate their movements during our experimental task, we expected these delays to also be present during timed clinical tests, such as the Jebsen Hand Function Test. Figure 8 (bottom) shows that reaction time strongly predicted Jebsen scores *only* in the RHD group. This suggests that “slower” performance in timed clinical tests following right hemisphere damage does not reflect slower movement, since our RHD group moved at the same peak velocities as our HC groups during our experimental task, but rather may be due to more time taken in preparing movement. Collectively, these findings demonstrate that similar functional deficiencies detected by clinical tests following left and right stroke could be attributed to impairment of different mechanisms specialized in each hemisphere.

DISCUSSION

The purpose of this study was to determine how left hemisphere damage (LHD) and right hemisphere damage (RHD) might contribute to ipsilesional deficits that could potentially impair functional performance in chronic stroke patients. Previous work from our laboratory in healthy young right-handed adults has suggested that the left (dominant) hemisphere may be specialized for predicting and accounting for the effects of intersegmental interactions acting at adjacent joints (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000), while the right (nondominant) hemisphere may be specialized for achieving accurate final positions (Bagesteiro & Sainburg, 2003; Duff & Sainburg, 2007; Sainburg, 2002). Thus, in the case of stroke patients with left or right hemisphere damage, we predicted that the ability to effectively coordinate elbow and shoulder motion would be impaired for the LHD group, and that the ability to achieve accurate final positions would be impaired for the RHD group.

Trajectory-based motor deficits following left, but not right, hemisphere damage

We found that although movement times were longer in both stroke groups relative to their control groups, movement speeds were only lower for the LHD group. Moreover, the hand trajectories for the LHD group were more curved relative to all other groups, and the degree of curvature varied more with the required direction of movement. We examined the relationship between the kinematics and joint torque during the initial portion of movement, and found that the LHD group showed greater variation in initial movement direction relative to variation in initial peak elbow muscle torque. These findings indicate that LHD patients can, and do, produce comparable magnitudes of muscle torque to healthy subjects; therefore, the slower movements and longer movement times we observed for these patients were not due to muscle weakness. Rather, these findings suggest that muscle torques generated at the elbow to accelerate the hand toward the target were not well coordinated with muscle torque generated at the shoulder and the resultant interaction torque in order to move the hand straight to the target. Previous studies have reported stroke-related changes in coordination patterns of elbow

and shoulder motion (Cirstea & Levin, 2000; Fang, Yue, Hrovat, Sahgal, & Daly, 2007; Levin, 1996) and torque (Beer et al., 2000) in the contralesional arm, but did not consider lesion side as a factor. Meanwhile, most studies that have quantified motor deficits based on lesion side have focused largely on temporal or kinematic changes following left or right hemisphere damage (Haaland & Flaherty, 1984; Haaland & Harrington, 1989a, 1989b; Haaland et al., 2004; Winstein & Pohl, 1995). The present study offers further insight, however, into the nature of hemisphere-specific motor deficits by examining plausible mechanisms that may give rise to such functional impairment, based on findings from healthy subjects. Dominant arm advantages for tasks requiring precise joint coordination, such as throwing and reaching, have been attributed to a dominant (left) hemisphere specialization for *effectively* predicting and compensating for interaction torques arising during multijoint movement under a variety of conditions by specifying appropriate muscle torque. The current study offers a direct test of this hypothesis, examining functional changes in the performance of the ipsilesional arm following left or right hemisphere damage.

We recently showed hemisphere-specific changes in movement strategy of the ipsilesional arm of left and right stroke patients for targeted single-joint reaching *without* changes in movement speed (Schaefer et al., 2007), but the degree to which those previous findings can generalize to more natural, multijoint movements was limited. However, we have now provided evidence for relating reduced movement speeds in the ipsilesional arm following left hemisphere damage to the reduced ability to predict and account for emergent interaction torques, which is consistent with the interpretation of Beer et al. (2000) for the contralesional arm. Moreover, the *lack of change* in movement speed and handpath curvature in the ipsilesional arm following right hemisphere damage suggests that the control mechanisms underlying these measures are lateralized, in part, to the left sensorimotor regions; this interpretation, however, requires additional investigation of stroke patients with and without sensorimotor damage, specifically.

Position-based motor deficits following right, but not left, hemisphere damage

In addition to hemisphere-specific changes in speed and trajectory, we also observed hemisphere-specific changes in final accuracy following stroke. More specifically, the RHD group made larger errors in final position relative to the target than the RHC group, despite having longer movement times and similar peak velocities; thus, impaired accuracy was not attributable to faster movement for the RHD group. Instead, we attribute such position-based deficits to right hemisphere damage, specifically. While studies in healthy adults and brain-damaged patients have provided substantial support for *left* hemisphere specialization for controlling aspects of *trajectory*, they have also offered considerable evidence for *right* hemisphere specialization for controlling aspects of *position*. The nondominant left arm of healthy right-handers appears to have an advantage for spatial accuracy relative to the dominant right arm, regardless of whether visual feedback is available (Guiard et al., 1983; Lenhard & Hoffmann, 2007), and has also been shown to have an advantage over the dominant right arm during inertial load compensation (Bagesteiro & Sainburg, 2003) and adaptation (Duff & Sainburg, 2007; Schabowsky et al., 2007). We hypothesized that such interlimb differences in position-based performance arise from a right (nondominant) hemisphere specialization for positional control; therefore, we predicted that following right but not left hemisphere damage, the accuracy of final position will be impaired for the ipsilesional arm. Patients with right, but not left, hemisphere stroke appear to have deficits in the deceleration phase just prior to target impact during rapid reciprocal aiming, particularly in conditions with high accuracy constraints (Winstein & Pohl, 1995), and without visual feedback. They also produce larger final position errors when reaching discretely across different distances (Haaland et al., 2004; Hermsdorfer et al., 2003; Schaefer et al., 2007).

Results from hemisphere-damaged patients in the current study are consistent with previous work (Reisman & Scholz, 2003), given that there were no differences in final accuracy relative to controls for the LHD group, while the RHD group was significantly less accurate across all movement directions relative to control subjects. It is, however, unlikely that these findings resulted from visual neglect. The RHD group systematically made straight, well-directed movements in the ipsilesional hemispace that were initiated with consistent patterns of joint torque, suggesting these patients accurately perceived the direction of the target relative to the start location. Larger errors in final position were due to the tendency of these patients to overshoot and/or undershoot the target, rather than to systematically bias their movements to the right, which might be expected in the presence of left hemispatial visual neglect. Only one of the 7 RHD patients demonstrated visual neglect, and the impairment was mild (i.e., the patient made 2 errors out of a possible 21 possible errors in the left hemispace). Furthermore, Darling et al. (2007) demonstrated in patients with and without right posterior parietal lesions that, during pointing movements, errors in perceiving target location were independent of errors in achieving accurate final positions. Thus, given the small number of patients with neglect and the mild degree of impairment, visual neglect is not a likely explanation of our findings. Instead, we attribute our hemisphere-specific deficits in final accuracy to the impaired ability to control limb position following right, but not left, hemisphere damage, which is consistent with our model of motor lateralization (Sainburg, 2002).

Clinical implications of left and right hemisphere damage

Because this study examined whether our model of motor lateralization could predict functional, hemisphere-specific motor deficits in the ipsilesional arm of left and right stroke patients, we used the Jebsen Hand Function Test (JHFT) to assess the degree to which functional performance was impaired in the ipsilesional arm. Many of the Jebsen tasks require arm coordination to ensure effective execution, such as checker-stacking and simulated feeding; thus, the JHFT also serves as a test of arm coordination (Jebsen et al., 1969). Consistent with previous findings, we found that ipsilesional JHFT performance was impaired to the same extent in our LHD and RHD groups. However, we found that *different aspects* of motor performance, in large part, accounted for longer JHFT times in our patient groups, depending on which hemisphere was damaged. More specifically, the amount of handpath curvature predicted Jebsen scores *only* in LHD patients, suggesting that changes in joint coordination following left hemisphere damage may be an underlying cause of poorer performance in clinical tests involving multijoint movements.

In contrast, reaction time predicted Jebsen scores *only* in RHD patients, such that the longer the reaction times were during reaching, the longer it took these patients to complete the Jebsen Hand Function Test (JHFT). The fact that these patients took longer to initiate their movements overall, but then moved at the same speed as control subjects did during our experimental task, suggests that “slower” performance in timed clinical tests following right hemisphere damage may not be due to slower movements, but may be due to more time taken *prior to* each movement instead. Our experimental findings are consistent with previous reports of increased reaction times following right, but not left, hemisphere damage for the ipsilesional (right) arm (Fisk & Goodale, 1988; Haaland et al., 2004; Harvey, Milner, & Roberts, 1994; Hermsdorfer et al., 1999; Smutok et al., 1989). It is plausible that the RHD group’s ability to produce well-coordinated movements may be due to effective planning of motor output by the intact left hemisphere, but at the cost of longer reaction times. Alternatively, Fisk & Goodale (1988) attributed longer reaction times following right hemisphere damage to difficulty in determining the position of the target in space, and interpreted their findings as support for a right hemisphere specialization for visuospatial processing (Benton & Tranel, 1993). However, Haaland et al. (2004) found no deficits in RHD patients when they were required to modify their movements in response to unpredictable changes in target location, suggesting that the

current findings are not due to visuospatial processing deficits after right hemisphere damage. It is unlikely that the increase in Jebsen scores for the RHD was due entirely to an increase in reaction time; we also reported impaired accuracy at final position in this group that may also influence performance on functional tests. Although we cannot, at this time, determine whether the RHD group in the current study had longer reaction times because they required more time to determine target location *or* to plan motor output prior to movement, we expected that if the RHD group took longer to initiate their movements during the experimental task, these delays should also be present during timed clinical tests, as exemplified in the current study.

In summary, these findings provide additional evidence for the separate control of trajectory and position during reaching, and suggest that such control mechanisms may be lateralized according to our model of hemispheric specialization. This study demonstrates that our hypothesis of “dynamic dominance” in healthy right-handed adults can predict functional, hemisphere-specific motor deficits in right-handed patients with left and right hemisphere damage, and reveals that similar functional deficiencies detected by clinical tests following left and right stroke can be attributed to impairment of different mechanisms specialized in each hemisphere. In order to further understand hemispheric specialization, however, additional research in non-right-handers is necessary to appreciate the degree to which motor control in healthy adults, and motor deficits in stroke patients, are lateralized.

ACKNOWLEDGEMENTS

This research was supported by the National Institutes of Health, National Institute for Child Health and Human Development (#RO1HD39311), National Institute on Aging training grant, Interdisciplinary Training in Gerontology (#T32AG00048), and the Department of Veterans Affairs Clinical Services Research and Development Merit Review grant and Rehabilitation Research and Development Merit Review grant B4125R. Further acknowledgments are to 1) Jennifer Hogan, Rena Singleton, and Monica Stump for data collection, 2) Drs. Robert Knight and Blaine Hart for MRI tracings and neuroanatomical consultation, 3) Dr. Joseph Sadek for statistical consultation, and 4) Drs. John Adair and Sally Harris, as well as HealthSouth Rehabilitation Hospital and Lovelace Medical Center, for patient referral.

REFERENCES

- Albert M. A simple test of visual neglect. *Neurology* 1973;23:658–664. [PubMed: 4736313]
- Bagesteiro LB, Sainburg RL. Handedness: dominant arm advantages in control of limb dynamics. *J Neurophys* 2002;88(5):2408–2421.
- Bagesteiro LB, Sainburg RL. Nondominant arm advantages in load compensation during rapid elbow joint movements. *J Neurophysiol* 2003;90(3):1503–1513. [PubMed: 12736237]
- Beer RF, Dewald JP, Dawson ML, Rymer WZ. Target-dependent differences between free and constrained arm movements in chronic hemiparesis. *Exp Brain Res* 2004;156(4):458–470. [PubMed: 14968276]
- Beer RF, Dewald JP, Rymer WZ. Deficits in the coordination of multijoint arm movements in patients with hemiparesis: evidence for disturbed control of limb dynamics. *Exp Brain Res* 2000;131(3):305–319. [PubMed: 10789946]
- Benton, AL.; Tranel, D. Visuo-perceptual, visuospatial, and visuoconstructive disorder. In: Heilman, KM.; Valenstein, E., editors. *Clinical Neuropsychology*. Oxford University Press; New York: 1993.
- Bloom JS, Hynd GW. The role of the corpus callosum in interhemispheric transfer of information: excitation or inhibition? *Neuropsychol Rev* 2005;15:59–71. [PubMed: 16211466]
- Bourbonnais D, Niven S, Vanden, Carey KM, Rymer WZ. Abnormal spatial patterns of elbow muscle activation in hemiparetic human subjects. *Brain* 1989;112(Pt 1):85–102. [PubMed: 2917281]
- Bovend'Eerd TJ, Dawes H, Johansen-Berg H, Wade DT. Evaluation of the Modified Jebsen Test of Hand Function and the University of Maryland Arm Questionnaire for Stroke. *Clin Rehabil* 2004;18(2):195–202. [PubMed: 15053129]
- Brinkman J, Kuypers HG. Splitbrain monkeys: cerebral control of ipsilateral and contralateral arm, hand, and finger movements. *Science* 1972;176(34):536–539. [PubMed: 4624322]

- Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain* 2000;123(Pt 5):940–953. [PubMed: 10775539]
- Darling WG, Bartelt R, Pizzimenti MA, Rizzo M. Spatial perception errors do not predict pointing errors by individuals with brain lesions. *J Clin Exp Neuropsychol* 2007;1–18. [PubMed: 17852587]
- DeArmond, S.; Fusco, M.; Dewey, M. Vol. 3rd ed.. Oxford University Press; New York: 1989. Structure of the human brain: a photographic atlas.
- Desrosiers J, Bourbonnais D, Bravo G, Roy PM, Guay M. Performance of the ‘unaffected’ upper extremity of elderly stroke patients. *Stroke* 1996;27(9):1564–1570. [PubMed: 8784131]
- Dewald JP, Pope PS, Given JD, Buchanan TS, Rymer WZ. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. *Brain* 1995;118(Pt 2):495–510. [PubMed: 7735890]
- Donchin O, Gribova A, Steinberg O, Mitz AR, Bergman H, Vaadia E. Single-unit activity related to bimanual arm movements in the primary and supplementary motor cortices. *J Neurophysiol* 2002;88(6):3498–3517. [PubMed: 12466464]
- Duff SV, Sainburg RL. Lateralization of motor adaptation reveals independence in control of trajectory and steady-state position. *Exp Brain Res* 2007;179(4):551–561. [PubMed: 17171336]
- Fang Y, Yue GH, Hrovat K, Sahgal V, Daly JJ. Abnormal cognitive planning and movement smoothness control for a complex shoulder/elbow motor task in stroke survivors. *J Neurol Sci* 2007;256(12):21–29. [PubMed: 17391704]
- Fisk JD, Goodale MA. The effects of unilateral brain damage on visually guided reaching: hemispheric differences in the nature of the deficit. *Exp Brain Res* 1988;72(2):425–435. [PubMed: 3224652]
- Frey R, Woods D, Knight R, Scabini D, Clayworth C. Defining functional areas with averaged CT scans. *Soc Neurosci* 1987;13:1266.
- Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Stegling S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scand J Rehabil Med* 1975;7(1):13–31. [PubMed: 1135616]
- Geffen GM, Jones DL, Geffen LB. Interhemispheric control of manual motor activity. *Behav Brain Res* 1994;64(12):131–140. [PubMed: 7840879]
- Gerloff C, Bushara K, Sailer A, Wassermann EM, Chen R, Matsuoka T, Waldvogel D, Wittenberg GF, Ishii K, Cohen LG, Hallett M. Multimodal imaging of brain reorganization in motor areas of the contralesional hemisphere of well recovered patients after capsular stroke. *Brain* 2006;129:791–808. [PubMed: 16364955]
- Given JD, Dewald JP, Rymer WZ. Joint dependent passive stiffness in paretic and contralateral limbs of spastic patients with hemiparetic stroke. *J Neurol Neurosurg Psychiatry* 1995;59(3):271–279. [PubMed: 7673955]
- Gordon J, Ghilardi MF, Cooper SE, Ghez C. Accuracy of planar reaching movements. II. Systematic extent errors resulting from inertial anisotropy. *Exp Brain Res* 1994;99(1):112–130. [PubMed: 7925785]
- Gordon J, Ghilardi MF, Ghez C. Accuracy of planar reaching movements. I. Independence of direction and extent variability. *Exp Brain Res* 1994;99(1):97–111. [PubMed: 7925800]
- Gribble P, Ostry D. Compensation for interaction torques during single- and multijoint limb movement. *J Neurophys* 1999;82:2310–2326.
- Guiard Y, Diaz G, Beaubaton D. Left-hand advantage in right-handers for spatial constant error: preliminary evidence in a unimanual ballistic aimed movement. *Neuropsychologia* 1983;21(1):111–115. [PubMed: 6843811]
- Haaland KY, Flaherty D. The different types of limb apraxia errors made by patients with left vs. right hemisphere damage. *Brain Cogn* 1984;3(4):370–384. [PubMed: 6085677]
- Haaland KY, Harrington DL. Hemispheric control of the initial and corrective components of aiming movements. *Neuropsychologia* 1989a;27(7):961–969. [PubMed: 2771034]
- Haaland KY, Harrington DL. The role of the hemispheres in closed loop movements. *Brain Cogn* 1989b;9(2):158–180. [PubMed: 2923708]
- Haaland KY, Harrington DL. Limb-sequencing deficits after left but not right hemisphere damage. *Brain Cogn* 1994;24(1):104–122. [PubMed: 7772095]

- Haaland KY, Harrington DL. Hemispheric asymmetry of movement. *Curr Opin Neurobiol* 1996;6(6): 796–800. [PubMed: 9000021]
- Haaland KY, Prestopnik JL, Knight RT, Lee RR. Hemispheric asymmetries for kinematic and positional aspects of reaching. *Brain* 2004;127(Pt 5):1145–1158. [PubMed: 15033898]
- Harrington DL, Haaland KY. Hemispheric specialization for motor sequencing: abnormalities in levels of programming. *Neuropsychologia* 1991;29:147–163. [PubMed: 2027431]
- Harvey M, Milner AD, Roberts RC. Spatial bias in visually-guided reaching and bisection following right cerebral stroke. *Cortex* 1994;30(2):343–350. [PubMed: 7924356]
- Hermisdorfer J, Blankenfeld H, Goldenberg G. The dependence of ipsilesional aiming deficits on task demands, lesioned hemisphere, and apraxia. *Neuropsychologia* 2003;41(12):1628–1643. [PubMed: 12887988]
- Hermisdorfer J, Laimgruber K, Kerkhoff G, Mai N, Goldenberg G. Effects of unilateral brain damage on grip selection, coordination, and kinematics of ipsilesional prehension. *Exp Brain Res* 1999;128(12): 41–51. [PubMed: 10473738]
- Hogan N. The mechanics of multi-joint posture and movement control. *Biol Cybern* 1985;52(5):315–331. [PubMed: 4052499]
- Hore J, O'Brien M, Watts S. Control of joint rotations in overarm throws of different speeds made by dominant and nondominant arms. *J Neurophysiol* 2005;94(6):3975–3986. [PubMed: 16120669]
- Hore J, Watts S, Tweed D, Miller B. Overarm throws with the nondominant arm: kinematics of accuracy. *J Neurophysiol* 1996;76(6):3693–3704. [PubMed: 8985867]
- Jebsen RH, Taylor N, Trieschmann RB, Trotter MJ, Howard LA. An objective and standardized test of hand function. *Arch Phys Med Rehabil* 1969;50(6):311–319. [PubMed: 5788487]
- Kawashima R, Yamada K, Kinomura S, Yamaguchi T, Matsui H, Yoshioka S, et al. Regional cerebral blood flow changes of cortical motor areas and prefrontal areas in humans related to ipsilateral and contralateral hand movement. *Brain Res* 1993;623(1):33–40. [PubMed: 8221091]
- Kertesz, A. Western Aphasia Battery. The Psychological Corporation; New York: 1982.
- Kim SG, Ashe J, Hendrich K, Ellermann JM, Merkle H, Ugurbil K, et al. Functional magnetic resonance imaging of motor cortex: hemispheric asymmetry and handedness. *Science* 1993;261(5121):615–617. [PubMed: 8342027]
- Kimura D, Archibald Y. Motor functions of the left hemisphere. *Brain* 1974;97(2):337–350. [PubMed: 4434181]
- Kuypers HG. The Descending Pathways to the Spinal Cord, Their Anatomy and Function. *Prog Brain Res* 1964;11:178–202. [PubMed: 14300477]
- Kuypers HG, Brinkman J. Precentral projections to different parts of the spinal intermediate zone in the rhesus monkey. *Brain Res* 1970;24(1):29–48. [PubMed: 4099987]
- Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *J Neurol Phys Ther* 2007;31(2):56–63. [PubMed: 17558358]
- Lenhard A, Hoffmann J. Constant error in aiming movements without visual feedback is higher in the preferred hand. *Laterality* 2007;12(3):227–238. [PubMed: 17454573]
- Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain* 1996;119(Pt 1):281–293. [PubMed: 8624689]
- Li A, Yetkin FZ, Cox R, Haughton VM. Ipsilateral hemisphere activation during motor and sensory tasks. *AJNR Am J Neuroradiol* 1996;17(4):651–655. [PubMed: 8730183]
- Liepmann H. Das Krankheitsbild der Apraxie. *Msschr. Psychiat. Neurol* 1900;8:15–44. 102–132, 182–197.
- Milner B, Kolb B. Performance of complex arm movements and facial-movement sequences after cerebral commissurotomy. *Neuropsychologia* 1985;23(6):791–799. [PubMed: 4080140]
- Phillips CG. The Ferrier lecture, 1968. Motor apparatus of the baboon's hand. *Proc R Soc Lond B Biol Sci* 1969;173(31):141–174. [PubMed: 4389426]
- Preilowski BF. Possible contribution of the anterior forebrain commissures to bilateral motor coordination. *Neuropsychologia* 1972;10(3):267–277. [PubMed: 5080490]
- Reisman DS, Scholz JP. Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis. *Brain* 2003;126(Pt 11):2510–2527. [PubMed: 12958080]

- Rinehart JK, Singleton RD, Adair JC, Sadek JR, Haaland KY. Arm use after left or right hemiparesis is influenced by hand preference. *Stroke* 2009;40:545–550. [PubMed: 19109543]
- Sainburg RL. Evidence for a dynamic-dominance hypothesis of handedness. *Exp Brain Res* 2002;142(2):241–258. [PubMed: 11807578]
- Sainburg RL. Handedness: differential specializations for control of trajectory and position. *Exerc Sport Sci Rev* 2005;33(4):206–213. [PubMed: 16239839]
- Sainburg RL, Ghez C, Kalakanis D. Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms. *J Neurophys* 1999;81(3):1045–1056.
- Sainburg RL, Ghilardi MF, Poizner H, Ghez C. Control of limb dynamics in normal subjects and patients without proprioception. *J Neurophys* 1995;73(2):820–835.
- Sainburg RL, Kalakanis D. Differences in control of limb dynamics during dominant and nondominant arm reaching. *J Neurophys* 2000;83(5):2661–2675.
- Sainburg RL, Poizner H, Ghez C. Loss of proprioception produces deficits in interjoint coordination. *J Neurophys* 1993;70(5):2136–2147.
- Sainburg RL, Schaefer SY. Interlimb differences in control of movement extent. *J Neurophys* 2004;92(3):1374–1383.
- Sainburg RL, Wang J. Interlimb transfer of visuomotor rotations: independence of direction and final position information. *Exp Brain Res* 2002;145(4):437–447. [PubMed: 12172655]
- Schabowsky CN, Hidler JM, Lum PS. Greater reliance on impedance control in the nondominant arm compared with the dominant arm when adapting to a novel dynamic environment. *Exp Brain Res* 2007;182(4):567–577. [PubMed: 17611744]
- Schaefer SY, Haaland KY, Sainburg RL. Ipsilesional motor deficits following stroke reflect hemispheric specializations for movement control. *Brain* 2007;130(Pt 8):2146–2158. [PubMed: 17626039]
- Schmit BD, Dhaer Y, Dewald JP, Rymer WZ. Reflex torque response to movement of the spastic elbow: theoretical analyses and implications for quantification of spasticity. *Ann Biomed Eng* 1999;27(6):815–829. [PubMed: 10625153]
- Semmes J. Hemispheric specialization: A possible clue to mechanism. *Neuropsychologia* 1968;6:11–26.
- Singh LN, Higano S, Takahashi S, Abe Y, Sakamoto M, Kurihara N, et al. Functional MR imaging of cortical activation of the cerebral hemispheres during motor tasks. *AJNR Am J Neuroradiol* 1998;19(2):275–280. [PubMed: 9504477]
- Smith JL, Zernicke RF. Predictions for neural control based on limb dynamics. *Trends Neurosci* 1987;10:123–128.
- Smutok MA, Grafman J, Salazar AM, Sweeney JK, Jonas BS, DiRocco PJ. Effects of unilateral brain damage on contralateral and ipsilateral upper extremity function in hemiplegia. *Phys Ther* 1989;69(3):195–203. [PubMed: 2919190]
- Sugarman H, Avni A, Nathan R, Weisel-Eichler A, Tiran J. Movement in the ipsilesional hand is segmented following unilateral brain damage. *Brain Cogn* 2002;48(23):579–587. [PubMed: 12030511]
- Sunderland A. Recovery of ipsilateral dexterity after stroke. *Stroke* 2000;31(2):430–433. [PubMed: 10657418]
- Sunderland A, Bowers MP, Sluman SM, Wilcock DJ, Ardron ME. Impaired dexterity of the ipsilateral hand after stroke and the relationship to cognitive deficit. *Stroke* 1999;30(5):949–955. [PubMed: 10229726]
- Tanji J, Okano K, Sato KC. Neuronal activity in cortical motor areas related to ipsilateral, contralateral, and bilateral digit movements of the monkey. *J Neurophysiol* 1988;60(1):325–343. [PubMed: 3404223]
- Vaughan HG Jr, Costa LD. Performance of patients with lateralized cerebral lesions. II. Sensory and motor tests. *J Nerv Ment Dis* 1962;134:237–243. [PubMed: 13925069]
- Vega-Gonzalez A, Granat MH. Continuous monitoring of upper-limb activity in a free-living environment. *Arch Phys Med Rehabil* 2005;86(3):541–548. [PubMed: 15759242]
- Wadman WJ, van der Gon J. J. Danier, Derksen RJA. Muscle activation patterns for fast goal-directed arm movements. *J Hum Mov Stud* 1980;6:19–37.

- Wetter S, Poole JL, Haaland KY. Functional implications of ipsilesional motor deficits after unilateral stroke. *Arch Phys Med Rehabil* 2005;86(4):776–781. [PubMed: 15827931]
- Winstein CJ, Pohl PS. Effects of unilateral brain damage on the control of goal-directed hand movements. *Exp Brain Res* 1995;105(1):163–174. [PubMed: 7589312]
- Winter, DA. *Biomechanics and Motor Control of Human Movement*. John Wiley and Sons; New York: 1990.
- Yelnik A, Bonan I, Debray M, Lo E, Gelbert F, Bussel B. Changes in the execution of a complex manual task after ipsilateral ischemic cerebral hemispheric stroke. *Arch Phys Med Rehabil* 1996;77(8):806–810. [PubMed: 8702376]

Figure 1.

Lesion locations were traced on 11 axial slices (see inset for slice level) from MRI or CT scans for each LHD (1-7) and RHD (1-7) patient. Slices are displayed left-to-right from inferior to superior (i-xi) for both groups of patients. Arrows in top row indicate location of central sulcus.

Figure 2.

A, Lateral and top view of experimental apparatus are shown. *B*, Experimental task required movement of cursor from start circle to 1 of 3 target circles located (*C*) in the medial, center, or lateral direction relative to the starting position. All targets were presented in the ipsilateral hemispace relative to the arm.

Figure 3.

The minor and major axes of the hand's trajectory for an example trial are schematically represented. The minor axis divided by the major axis is used as a measure of handpath curvature for a given trajectory.

Figure 4.

A, Mean reaction time B, Mean movement time C, Mean absolute error and D, Mean peak tangential velocity for each target is displayed for the left and right arms of control subjects (LHC,RHC) (solid line) and the ipsilesional arms of left- and right-hemisphere-damaged patients (LHD,RHD) (dashed line). Bars indicate standard error of mean.

Figure 5.

A, Handpaths of individual trials to each target are shown for a representative subject from each group. B, Mean handpath curvature for each target is displayed for the left and right arms of control subjects (LHC,RHC) (solid line) and the ipsilesional arms of left- and right-hemisphere-damaged patients (LHD,RHD) (dashed line). Bars indicate standard error of mean.

Figure 6.

A. Handpaths of two trials to the medial target for a LHD and RHD patient are shown. These handpaths correspond to the trials initiated in the most positive, or clockwise (CW) (gray), and most negative, or counter-clockwise (CCW) (black), directions for each patient relative to a right-arm coordinate system. The cross-hairs indicate the location of the fingertip 100 ms following movement onset. B. Mean standard deviation (SD) of initial movement direction for the medial target is displayed for the left and right arms of control subjects (LHC, RHC) (solid line) and the ipsilesional arms of left- and right-hemisphere-damaged patients (LHD, RHD) (dashed line). Bars indicate standard error of mean. C. The profiles of corresponding shoulder muscle (top), elbow interaction (middle), and elbow muscle (bottom) torque are displayed for the first 100 ms of each trial. Arrows indicate initial peak elbow muscle torque, as defined as the maximum torque (flexor or extensor) generated during the first 100 ms. D. Mean coefficient of variation (CV) of initial peak shoulder muscle (top), elbow interaction (middle), and elbow muscle (bottom) torque for the medial target is displayed for the left and right arms of control subjects (LHC, RHC) (solid line) and the ipsilesional arms of left- and right-hemisphere-damaged patients (LHD, RHD) (dashed line). Bars indicate standard error of mean.

Figure 7.

A, The location of the hand at peak velocity (+) and movement end (●) for each trial of an LHD patient and RHD patient are shown. Ellipses represent the 99% confidence interval of the data from each target for each patient. B, Mean ratio of variable error at peak velocity relative to movement end collapsed across targets is displayed for the left and right arms of control subjects (LHC,RHC) (solid) and the ipsilesional arms of left- and right-hemisphere-damaged patients (LHC,RHD) (lined). Bars indicate standard error of mean.

Figure 8.

Jebsen Hand Function test score is plotted as a function of mean handpath curvature (top) and mean reaction time (bottom) collapsed across targets for each subject in each group (dot). Corresponding r^2 values are displayed in the bottom left corner of each scatterplot.

Table 1

Summary of participant information

Subject	Sex	Age (yrs)	Education (yrs)	Post- stroke (yrs) ^a	Lesion volume (cm ³) ^b	UE Fugl- Meyer ^c	Auditory Comprehension ^d	Limb apraxia ^e	Grip strength right/ left ^f	Jebson Hand Function score (s) ^g	Lesion location ^h
LHD1	M	44	14	7.0	147	22	46	10	0	51	SMC, IC, BG,
LHD2	M	60	14	16.8	29	45	80	14	12	54	IC, BG, PC
LHD3	M	46	17	5.1	153	61	80	14	27	48	SMC, IC, BG,
LHD4	M	61	14	17.3	125	27	66	11	12	44	SMC, IC, BG,
LHD5	M	65	18	9.8	231	7	36	10	0	47	SMC, IC, BG,
LHD6	M	55	14	0.7	24	10	44	9	0	62	IC, BG
LHD7	M	76	12	12.0	114	33	80	11	9	46	SMC, PC
<i>mean ± SD</i>		<i>58.1 ± 11.1</i>	<i>14.7 ± 2.1</i>	<i>9.8 ± 6.1</i>	<i>117.5 ± 72.7</i>	<i>29.3 ± 19.1</i>	<i>64.4 ± 21.7</i>	<i>11.6 ± 1.3</i>	<i>50.3 ± 6.1</i>	<i>81.3 ± 23.7</i>	
RHD1	M	63	12	3.7	159	2	80	12	58	0	SMC, IC, BG,
RHD2	M	50	14	19.5	245	4	80	11	24	0	SMC, IC, BG,
RHD3	M	81	16	5.0	39	14	80	10	27	5	SMC, CP
RHD4	M	52	12	10.5	275	49	80	14	34	5	SMC, PC, DLPF
RHD5	F	58	16	9.0	137	6	80	11	33	0	SMC, IC, BG,
RHD6	M	63	18	3.8	119	5	80	12	38	0	SMC, IC, BG,
RHD7	M	55	16	5.9	283	6	80	11	36	0	SMC, IC, BG,
<i>mean ± SD</i>		<i>60.3 ± 10.4</i>	<i>14.9 ± 2.3</i>	<i>8.2 ± 5.6</i>	<i>179.5 ± 91.1</i>	<i>12.3 ± 16.6</i>	<i>80.0 ± 0</i>	<i>11.3 ± 2.0</i>	<i>35.7 ± 11.0</i>	<i>1.4 ± 2.4</i>	<i>75.4 ± 28.9</i>

^aYears post-stroke are calculated as time elapsed between incidence of stroke and day of data collection.

^bLesion volume is computed from MRI using a computer algorithm.

^cUpper-extremity (UE) motor subscore of the Fugl-Meyer Motor Assessment is 66.

^dLanguage comprehension was assessed using the Western Aphasia Battery.

^e Apraxia is designated as mean number correct out of 15 items using a validated apraxia battery.

^f Grip strength from dynamometer are expressed as standardized *t* scores.

^g Score is elapsed time for completion of 7-item Jebsen Hand Function test.

^h SMC=Somatomotor cortex [Brodmann Areas (BA) 4, 6, and/or 3,1,2]; IC=Internal Capsule; BG=Basal Ganglia; PC=Parietal Cortex [BA=39, 40, and/or 7]; DLPF=Dorsolateral Prefrontal cortex [BA 8, 9, and/or 46].