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Characterization of Motor Adaptation and Limb Posture Regulation During Arm Reaching Movements Following Stroke

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Abstract:

Whether attempting to pour water into a handheld glass, or simply trying to hold a young child's hand, many activities of daily living require interaction with unpredictable or uncertain mechanical environments. Here we describe a systems identification study that used a planar manipulandum to characterize how hemiparetic stroke survivors adapt reaching movements to novel mechanical environments. By analyzing trial-by-trial variations in hand path kinematics, we found that stroke survivors are less likely than neurologically-intact subjects to adjust motor commands for upcoming movements based on hand trajectory errors experienced on previous trials. This ability is most significantly compromised in subjects with Fugl-Meyer scores /spl les/ 20. The ability to terminate movement accurately at the desired target was significantly compromised on the impaired side for most stroke survivors. This measure of performance contrasts with the trajectory updating measure in that it did not depend on impairment level. These data suggest that stroke survivors vary in their ability to effectively adapt motor commands based on recent sensorimotor experience. The findings also provide indirect support for the hypothesis that final posture regulation and feedforward trajectory control are complimentary processes that may be differentially compromised following stroke.

SECTION I. Introduction

HEMIPARESIS of the upper limb is a frequent consequence of stroke that limits a survivor's independence and health. Disabilities of the upper extremity arise for several reasons, including deficits in the ability to individuate joint movements, lack of strength and sensation, and impaired coordination between limb segments [1]–[2]. Studies of subjects with “chronic” hemiparesis (>6 month post-stroke) have noted improved functional limb movements with practice [3] as well as cortical reorganization and recruitment following intensive use of the affected limb [4]. Thus, arm-focused training may facilitate motor relearning well beyond the acute phase of recovery [5].

It has been proposed that recovery of motor function may be facilitated, in part, by training that exploits motor adaptation [6]. Motor adaptation is an important form of motor learning whereby nominal performance of a motor task is recovered following onset of an externally-imposed, disturbance. Preliminary studies of motor adaptation following hemiparetic stroke reveal that these patients often retain the ability to adapt to altered mechanical environments with the impaired limb [6]. A more thorough knowledge of adaptive motor process(es) will likely be necessary to guide optimization of functional recovery following stroke.

Here we describe experiments using a planar robot to characterize how hemiparetic stroke survivors and neurologically-intact individuals adapt reaching movements to novel mechanical environments. We used systems identification techniques previously developed to model motor adaptation in unimpaired subjects [7] to characterize adaptation to viscous curl force fields. We tested the hypothesis that the ability to adjust movements based on errors experienced on recent trials decreases as the degree of sensorimotor impairment increases. If true, then systems identification techniques such as those described below may be helpful in identifying those subjects most likely to benefit from practice and adaptation-based rehabilitation.

SECTION II. Methodology

A. Human Subjects

12 unilateral, hemiparetic stroke survivors (SS) and 11 neurologically-intact (NI) subjects gave informed consent to participate in this study in compliance with policies established by Marquette University's Office of Research Compliance and Northwestern University's Office for Protection of Research Subjects. All but one of the stroke survivors were in the chronic stage of recovery, (at least 6 months post-stroke). One severely-impaired subject was only 2 months post-stroke. These individuals were recruited from the pool of hemiparetic outpatients of the Rehabilitation Institute of Chicago and ranged in age from 38 to 79 years (mean: 56.0). Neurologically-intact individuals were volunteers ranging in age from 22 to 58 years (mean: 48.3).

B. Clinical Assessments

Immediately prior to each experimental session, the motor function for each hemiparetic subject was assessed by a physical therapist using a battery of clinical assessment tools including: the modified Ashworth Spasticity

Scale, the Fugl-Meyer motor performance scale (upper extremity portion), and reaching components of the Wolf Motor Function and the Arm Motor Ability Tests. Impairment measures were also taken, including active and passive range of motion at the shoulder, elbow, and wrist, and assessment of the appreciation of light touch and proprioception. Premorbid hand dominance and stroke location were obtained via self-report. With the subject's written approval, medical records were reviewed to corroborate lesion site information. Subjects were assigned to one of four broad categories based on their Fugl-Meyer scores: Severely impaired (FM: 0 to 20; n=4), moderately impaired (21<FM<50; n=4),FM: 50+; n=4), and unimpaired (neurologically intact; NI; n=11).

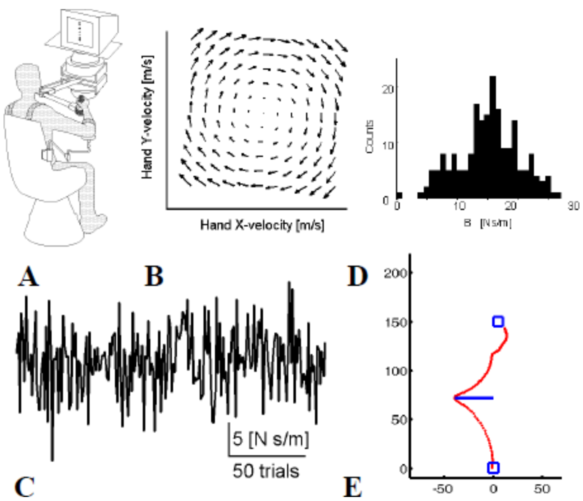

Fig. 1. Experimental protocol for preliminary experiment. A) Subject position relative to the manipulandum. B) Force field used to perturb the subject's limb. C) Sequence of gains used to scale perturbation of panel B on a trial-by-trial basis. D) Histogram of perturbation amplitudes from the trial sequence in panel C. E) Trajectory error was calculated as the peak perpendicular distance [mm] from a straight-line passing between the initial (bottom) and final (top) targets (10 mm squares)

C. Experimental Protocol

Subjects were strapped into a high-backed chair with a chest harness designed to minimize trunk movement. The arm being tested was supported against gravity (70–90° abduction angle) with a light-weight, chair-mounted, mobile arm support. Subjects grasped the handle of a two-joint robotic manipulator and performed 10–15 cm reaches between 2 targets in the horizontal plane (Fig 1A). “Beginning” and “end” targets were projected onto an opaque screen mounted just above the robot's plane of motion. The screen occluded direct view of the arm and hand. However, a small cursor was projected onto the screen and it moved directly above the hand at all times. Subjects were instructed to “reach from initial to final target” with a peak hand speed of 0.5 m/sec. Feedback of hand speed was provided following each movement as either too fast (> 0.6 m/sec), too slow (< 0.4 m/sec) or just right.

50 movements of the arm contralateral to the lesion site (non-dominant arm for NI subjects) were first made without perturbation allowing subjects to practice the task. Subjects then made 200 “test” movements wherein velocity-dependent hand forces were applied during the i-th movement (1):

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = B_i \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \quad (1)$$

FX and FY were the components of force applied by the robot along the left/right (x) and proximal/distal (y) directions (Fig 1B). Bi was a random real number between 0 and 30 Ns/m such that the amplitude (but not the direction) of the perturbing force field varied randomly from trial to trial (Fig 1C). Since movements were always directed away from the body along a line (the positive Y-axis) passing through the shoulder center of rotation, the perturbing forces were always directed to the left. The environment impedance changed only between trials. The distribution of perturbations had a non-zero mean (15.2 Ns/m) corresponding to information about the perturbation sequence that subjects might learn (Fig. 1D). The random sequence was designed to insure insignificant correlation between perturbation magnitudes on consecutive trials. After each movement had concluded, the robot moved the relaxed limb back to the initial starting location. Subjects then repeated the testing with their ipsilateral (or dominant) arm.

D. Data Analysis

We quantified performance using kinematic measures of trajectory error (defined as the peak deviation from a straight-line hand path between initial and final targets; Fig 1E) and final position error (the Euclidean distance between the hand's final resting location and the center of the final target). We characterized trial-by-trial adjustments to hand trajectory using a technique developed to characterize motor adaptation in neurologically intact subjects [7]. Specifically, we regressed the trial-to-trial variations of trajectory error onto error from the most recent attempt (e_{i-1}) as well as onto current and previous perturbation magnitudes (B_i and B_{i-1}):

$$e_i = a_1 e_{i-1} + b_0 B_i + b_1 B_{i-1} \quad (2)$$

where a_1, b_0 and b_1 are coefficients weighting the relative importance of the regressors on subsequent errors. This model is a limited-memory, autoregressive process with external input (an ARX structure [8]). A multilinear regression was performed to derive parameter values specific to each subject. The z-transform of (2) suggests that motor adaptation has relatively simple first-order dynamics:

$$H(z) = b_0 \left(z + \frac{b_1}{b_0}\right) / z - a_1 \quad (3)$$

with a single pole located at $z = a_1$ and a single zero located at $z = -b_1/b_0$. ANOVA and post-hoc t-tests were performed to evaluate the presence of systematic differences in pole and zero locations between subject groups (SS vs. NI) and between levels of impairment within the SS group.

Since the unpredictable perturbations used in this study had no static component of force, degradation of terminal accuracy implies compromise to the mechanisms regulating the limb's final posture. We tested the hypothesis that final limb posture regulation is compromised following hemiparetic stroke by estimating the 95% confidence interval ellipses for each hand's final position using principal component analysis [9]. The area subtended by these ellipses was compared within each subject to evaluate how well final limb posture was regulated in the impaired vs. unimpaired limbs. ANOVA was performed to evaluate the presence of systematic differences in final limb posture regulation between levels of impairment within the SS group.

Table I Clinical Evaluation of Hemiparetic Subjects

Subj	Age	Sex	Years post CVA	Stroke location	Premorbid handedness	Paretic side	Proprioception	Impairment severity	Other issues
1	38	M	6	R	R	R	Impaired	Mild	L hemianopsia
2	70	M	14	R SAH	R	L	Intact	Severe	Double vision
3	51	F	6	R	R	L	Intact	Moderate	
4	63	F	14	L lacunar	R	R	Intact	Moderate	
5	68	M	6	R	R	L	Intact	Mild	
6	54	M	11	L	R	R	Absent	Severe	
7	44	F	5 & 6	R	R		Intact	Severe	Hand dystonia
8	59	F	2 mo	R	R	R	Intact	Severe	Difficulty isolating elbow ext
9	46	M	4	L frontal lobe	R	L	Impaired	Moderate	
10	53	M	6 mo	L MCA	R	R	Intact	Severe	Required strong manual trunk stabilization
11	47	M	2	L	R	R	Intact	Moderate	
12	79	F	6	L	R	R	Intact	mild	

SECTION III. Results

A. Clinical Assessment

The 12 stroke survivors who participated in this study were evenly distributed between the mild-, moderate-, and severely-impaired subgroups (Table 1). These subjects formed a heterogeneous set. The time post-stroke ranged from 2 months to 14 years. The locus of stroke varied considerably. Proprioception ranged from entirely absent to intact. Nevertheless, systematic changes in hand trajectory were observed in all stroke survivors: Almost all stroke subjects were incapable of moving smoothly and directly to the target (Fig. 2), even in the absence of external perturbations (data not shown). Hand trajectories for both the contralateral and ipsilateral limbs were frequently segmented or “cusped”, having multiple hand speed maxima.

B. Trajectory Formation

The degree to which prior movement errors influence subsequent movements is captured by the location of the system pole of model (3). After performing multilinear regression, we analyzed the residuals of fit and found them to be normally distributed about zero, suggesting that the ARX model of (3) neither over-fit or under-fit the dataset. We performed ANOVAs and post-hoc Tukey t-tests to evaluate whether there existed systematic differences in pole location across subject groups (SS vs. NI) and between the ipsilateral and contralateral limbs of SS (Fig. 3A). Parameter a1 does indeed differ between subject groups ($F=6.02$; $p=0.01$; Fig. 3A) such that prior movement errors influenced subsequent movements to a lesser degree in both limbs of the stroke survivors than in NI subjects. Parameter a1 also appears to vary with impairment level ($F=5.39$; $p = 0.01$; Fig. 3B), with the most severely impaired limbs showing little or no carry-over of hand path error estimates from one movement to the next. No significant differences in zero location of model (3) were observed between subject groups or between limbs in either group. Also, regression analyses found no relationship between age and any model parameter in unimpaired subjects (dominant and nondominant limbs).

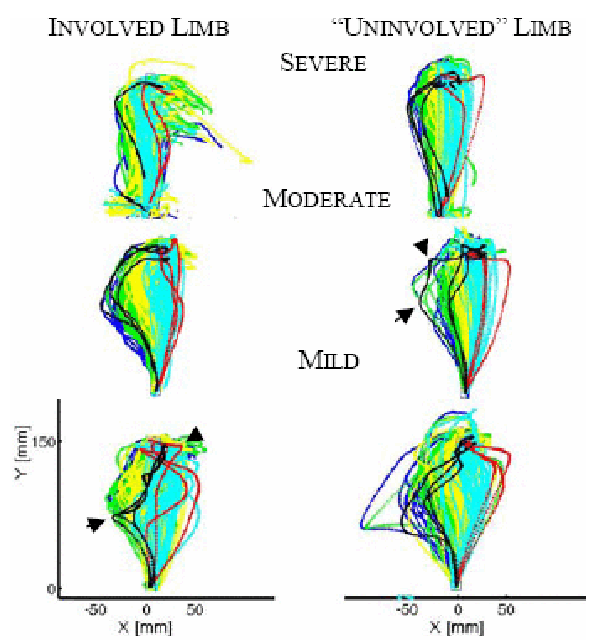

Fig. 2. Hand paths from the involved (left column) and uninvolved (right column) limbs of representative subjects from the three impairment levels. Each of these subjects compensated for the CCW curl perturbation with the uninvolved limb, compensation was not always evident on the involved side. The severely impaired subject produced wildly erratic movements with this limb while subjects scoring 21+ on the Fugl-Meyer produced movements that varied more systematically with perturbation magnitude. Movements in the strongest fields are color-coded black, while movements in the weakest fields are color-coded red. Many of the

movements in both limbs exhibit “cusp-points” (arrow heads) consistent with the presence of multiple peaks in the hand speed profile

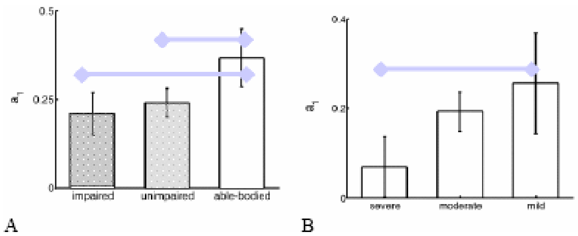

Fig. 3. Comparison of model parameter a1 across limbs (A) and across impairment levels (B). Error bars indicate +/-2 SEM. Significant differences between conditions (identified via ANOVAs and post-hoc tests) are indicated by the horizontal bars above the bar charts

C. Regulation of Final Hand Position

Nine of 12 SS had difficulty in acquiring the final target with the contralateral limb (Fig 4). Trial-by-trial variation in final hand position was significantly higher in this limb compared to limbs of NI subjects (ANOVA: $F=4.81$; $p=0.02$). Final position variability varied considerably across SS in the ipsilateral limb, with some subjects performing equally poorly with both “uninvolved” and involved limbs. ANOVA revealed no significant relationship between final position variability and impairment level in the involved limb.

Fig. 4. Analysis of final hand position with the involved limb (left) and uninvolved limb (right) of a representative stroke survivor. Blue boxes represent the final target locations which were 1 cm in height and width. All SS exhibited large variability in the final position of the more-impaired hand

SECTION IV. Discussion

Eight of 12 stroke survivors tested in this study retained an ability to execute trial-by-trial adjustments in motor performance. This behavior is consistent with the limited-memory model of motor adaptation previously shown to capture features of motor adaptation such as reduction in hand trajectory errors and the generation of “mirror-symmetric catch trial errors” in unimpaired individuals [7]. Here we have shown that the extent to which trial-to-trial adjustments in motor programs depend on prior estimates of hand path errors varies systematically with the level of impairment assessed clinically by the Fugl-Meyer. These findings support and extend the findings that both improvements in arm reaching performance with short-term practice [10] and motor performance of the arm [11] depend on the severity of the motor deficit in stroke.

In contrast, the ability to bring one's hand to rest accurately at a final target location was compromised in most subjects and it did not appear to vary systematically with impairment severity. Movements made by all stroke subjects were frequently segmented (cf. [12]), exhibiting multiple “cusp points” coinciding with local minima in the hand speed profiles. Segmentation of movement may reflect an inability to integrate a feed-forward specification of movement parameters (such as direction and extent) with online feedback regulation of the hand's desired final location. Differentially impaired posture and movement regulation provides indirect support for the notion that these aspects of control may be mediated by separate neural substrates [13].

SECTION V. Summary

We found that: a) as a group and for both limbs, stroke survivors are less able to integrate prior movement error information into coordinated adjustments to subsequent movements; b) this ability scales with impairment level (as quantified clinically by Fugl-Meyer scores); c) final position regulation was significantly compromised on the impaired side for most stroke survivors; and d) the variability of final hand position did not vary systematically with Fugl-Meyer.

These findings are important because they suggest that not all stroke survivors retain the ability to adapt motor commands using performance information from previous movement attempts. Consequently, the techniques described here may be helpful in identifying subjects most likely to benefit from practice and adaptation-based therapies. Finally, the data support the idea that the neural mechanisms regulating movement and posture may be differentially compromised following stroke, and may therefore require specialized therapeutic techniques for their rehabilitation.

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