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Submovements During Reaching Movements After Stroke

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Abstract: Neurological deficits after cerebrovascular accidents very frequently disrupt the kinematics of voluntary movements with the consequent impact in daily life activities. Robotic methodologies enable the quantitative characterization of specific control deficits needed to understand the basis of functional impairments and to design effective rehabilitation therapies. In a group of right handed chronic stroke survivors (SS) with right side hemiparesis, intact proprioception, and differing levels of motor impairment, we used a robotic manipulandum to study right arm function during discrete point-to-point reaching movements and reciprocal out-and-back movements to visual targets. We compared these movements with those of neurologically intact individuals (NI). We analyzed the presence of secondary submovements in the initial (i.e. outward) trajectory portion of the two tasks and found that the SS with severe impairment (FM <; 30) presented arm submovements that differed notably not only from NI but also from those of SS with moderate arm impairment (FM 30-50). Therefore the results of this pilot study suggest that in SS arm kinematics vary significantly across differing levels of motor impairment.

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Our results support the development of rehabilitation therapies carefully tailored to each individual stroke survivor.

SECTION I.

Introduction

Stroke is the leading cause of disability worldwide. In particular, motor deficits in the arm are a very frequent longterm sequela after stroke. Thus the understanding of the altered kinematics of arm mobility is a cornerstone for the development of appropriate therapeutic interventions. In recent years, the incorporation of new robotic and advanced digital technologies has enabled more precise quantitative assessments of arm function.[1–2,3,4] The analysis of secondary submovements in chronic stroke survivors (SS) is important because on the one hand, increased frequency of submovements has been described in association with low movement speed which is also typical of aging and Parkinson's disease,[5,6] and on the other hand, the observed decrease in the frequency of submovements after therapeutic interventions has been proposed to characterize motor recovery after stroke.[7,8] Secondary submovements are present in neurologically intact individuals and their origin is a matter of debate.[5,9] Interestingly, it has been hypothesized that submovements are the "building blocks" of movements, that is, during motor learning submovements blend as the movements become smooth and more accurate when the task begins to be mastered.[7,10] Here we report differences in the amount and type of submovements in two groups of SS with differing levels of motor impairment performing reaching movements. Most studies on motor function after stroke, whether small or large-scale, consist of heterogeneous groups of SS (e.g. different levels of motor impairment), our initial findings point to the importance of studying arm kinematics in separate well characterized groups of SS

SECTION II.

Methods

A. Subjects

From a group of thirteen SS, we selected a group of six unilateral, right side hemiparetic stroke survivors, right handed with intact proprioception and Fugl-Meyer scores (FM) between 20 and 50 (SS; aged 38–73 years; Table 1). A group of six age-range-matched neurologically intact (NI) control subjects who were able to achieve the test position without discomfort were recruited for the study. All subjects gave written informed consent to participate in this study in compliance with policies established by Northwestern University Office for Protection of Research Subjects. All SS were in the chronic stage of recovery (> 6 months post-stroke); they were recruited from a database of hemiparetic stroke outpatients maintained by the Rehabilitation Institute of Chicago. All SS also provided written consent allowing medical record review. Exclusion criteria included: <6 months post-stroke, multiple strokes, inability to give informed consent, inability to follow 2-step directions, history of tendon transfer in the involved limb, neurological or muscular disorder that might interfere with neuromuscular function, recent use (within the previous 8 months) of curare-like agents or other agents that may interfere with neuromuscular function, and/or shoulder pain in the test position of 75° to 90° abduction. All subjects participated in two experimental sessions, each lasting ~2.0 h (including setup time).

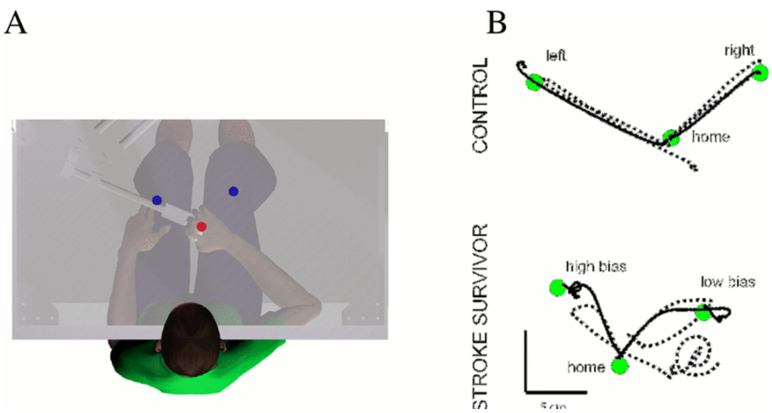

Figure 1. A: Experimental setup. B: Trajectories of point-to-point (solid line) and out-and-back (dashed line) movements of control and stroke survivor participants.

B. Clinical Assessments

All SS participated in an initial consenting/evaluation session prior to experimentation. During this session, motor function and impairment level was assessed by the same clinician while the subject was seated in an armless chair. Clinical assessments included: 1) visual field evaluation and visual search task; 2) the upper extremity portion of the Fugl-Meyer (FM) Assessment of Physical Performance to assess motor control;[11] 3) the Modified Ashworth Scale (MAS) to assess spasticity at the shoulder, elbow, and wrist; 4) grip strength; and 5) clinical evaluation of tactile and proprioceptive discrimination deficits.[2] To obtain an overall estimate of spasticity of the upper extremity, the MAS scores were averaged across the joints tested.[12]

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SS were further divided into one group of three participants who exhibited moderate motor impairment (FM > 30) and another group of three participants with more severe motor impairment (FM < 30). Of note, those participants with severe motor deficits exhibited moderate levels of arm spasticity as measure with the MAS (Table 1).

Table I. Clinical assessments for stroke survivors

Age/Sex	Years Post-CVA	FM	MAS	Grip*	Touch	Proprio
54/F	5	45	0.33	18	I:F,H,FA, U	N
40/M	6	43	0.66	35	N	N
69/F	6	41	0	4	I:F,H	N
60/F	14	28	1.83	8	N	N
72/F	20	23	1.66	4	N	N
59/F	5	22	1.66	5	N	N

* Grip force units are in Kilograms

Abbreviations: FM: Fugl-Meyer; MAS: Modified Ashworth Score; N: not impaired; I: impaired; F: finger; H: hand; FA: forearm; U: upper arm; Proprio: proprioception.

C. Experimental Procedures and Tasks

Subjects were seated in a high-backed chair fixed in front of a horizontal planar robot (Fig 1A).[2] The robot monitored instantaneous hand position and reaction forces at the handle. A chest harness was strapped across the subject's shoulders to minimize trunk motion. The arm was supported against gravity (between 75° and 90° abduction; ~45° horizontal flexion) using a lightweight, chair-mounted arm support. The wrist (SS: paretic right side; NI: right side) was splinted at 0° flexion and fixed to the robot's hemi-spherical handle with Velcro® straps. Subjects moved the instrumented handle of the robot with their dominant right hand between targets projected onto an opaque screen lcm above the plane of movement. This screen occluded vision of arm, hand, and robot. A drape covering the shoulder and upper arm prevented subjects from seeing their shoulder and upper arm. During the experiments, textual messages were displayed on the horizontal screen to reinforce verbal instructions. Upper arm and forearm segment lengths were measured in each subject as was the shoulder center of rotation relative to the origin of the robot's workspace.

Each subject performed two tasks, a point-to-point reaching task (reaching) and out-and-back movement task (reversal) that required moving the hand from a central starting position to one of two radial targets projected in the horizontal plane (Fig. 1). In

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the reaching task (164 trials), subjects moved the handle to the target and held it stationary for 1.5 s (Fig. 1 B). In the reversal task (164 trials), subjects moved out-and-back along a line reversing direction within the target without pausing at the target (Fig. 1 B). Both tasks were performed under two conditions: in the full vision condition trials, the cursor indicating hand position was visible throughout movement; in the blind condition trials, there was no visual feedback during movement, the cursor position was shown only at the end of the movement; for the reaching task, this position corresponded to the end of the movement while for the reversal task, it corresponded to the point of reversal. After each movement, subjects were provided with a visual indicator of peak speed and were instructed to maintain it around the same value (0.4 m/s) in both tasks. At the end of each trial the cursor was blanked and the robot returned the hand passively to the start position.

D. Kinematic and Data Analyses

Instantaneous hand position was recorded at 1000 samples/s using 17 -bit rotational encoders mounted on the robot's motors. We identified kinematic features using an automated algorithm within the MATLAB programming environment. Each was verified visually and was manually adjusted if necessary.

Following Dounskaia and colleagues[6] we use a method suggested by Meyer[13] that distinguishes three types of secondary submovements: Type 1 results from a zero crossing (from positive values to negative) in the velocity profile and could be interpreted as representing reversals in the trajectory; type 2 results from a zero crossing (from negative to positive) in the acceleration profile and could be interpreted as a reacceleration towards the target (Fig. 2 B); Type 3 results from multiple zero crossing in the jerk profile and could be interpreted as a decrease in the rate of deceleration (Fig. 2 C).

It has been shown that the majority of gross (type 1) submovements emerge during motion termination.[6,13] The origins of the fine (type 2 and 3) submovements are more controversial, Dounskaia and colleagues[5,6] defend that they are not just corrective movements but represent velocity fluctuations. For those reasons, in the present study we focused on the emergence of secondary submovements during the outward trajectory phase of the reaches and reversals, and did not analyze the stabilization phase of these movements. That is, our analysis focused on the emergence of secondary submovements, for point-to-point reaching movements (reaches) and the outward phase of out-and-back movements (reversals), during the portion of the movement between its onset, when the hand velocity first exceeded 0.1 m/s at the beginning of the trial, and its offset, when the hand velocity went below 0.1 m/s (marked by the green squares in Fig. 2).

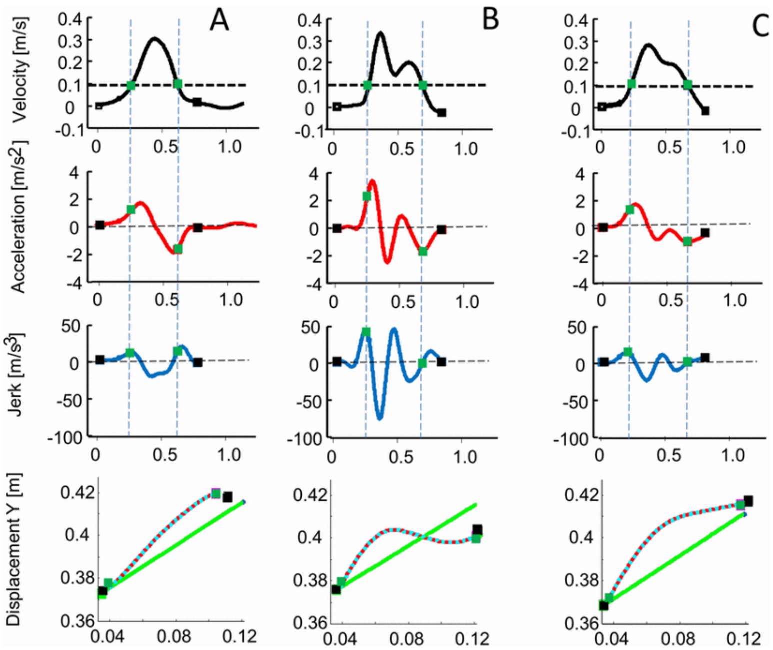

Figure 2. Velocity, acceleration, and jerk profiles for representative point-to-point reaching movements from a SS with severe impairment (fm 28). A: Normal reach. B: Reach with type 2 submovement. C: Reach with type 3 submovement.

We considered "normal" reaches and reversals when there was no presence of secondary movements (Fig. 2 A), and reaches and reversals with type 1, 2, or 3 secondary submovements as defined above. For each subject, we computed the incidence of secondary submovements by type as the number of movements with a secondary submovement of the respective type divided by the total number of movements performed under each condition. We did this calculation separately for reaches and reversals, distinguishing whether they were performed under full vision or blind conditions (Fig. 3).

A three-way analyses of variance (ANOV A) was used to compare each performance measure (i.e. normal, type 2 submovement and type 3 submovement) considering the following 3 fixed factors: 1) Movement type (reach, reversal); 2) Level of impairment (NI, SS with FM > 30, SS with FM < 30); and 3) Trial condition (full vision, blind). If significant effects were found (α=.05) a post-hoc analysis was performed using Tukey's honestly significant difference criterion (HSD) test.

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SECTION III.

Results

All subjects exhibited type 3 secondary submovements during the execution of reaches and reversals under full vision and blind conditions. However, type 2 secondary submovement emerged only occasionally in the movements executed by NI subject and SS with moderate impairment, while the incidence of type 2 submovements was higher in the group of SS with severe impairment (Fig. 3 FM $<$ 30).

None of the subjects presented movements with type 1 secondary submovements.

The multi-factorial ANOV As revealed a main effect of level of impairment on type 2 submovements (F2.36=4.98,p=0.012) and our post-hoc analysis confirmed that the incidence of type 2 submovements was significantly higher in the group of SS with severe impairment (p<0.05; Tukey's HSD test).

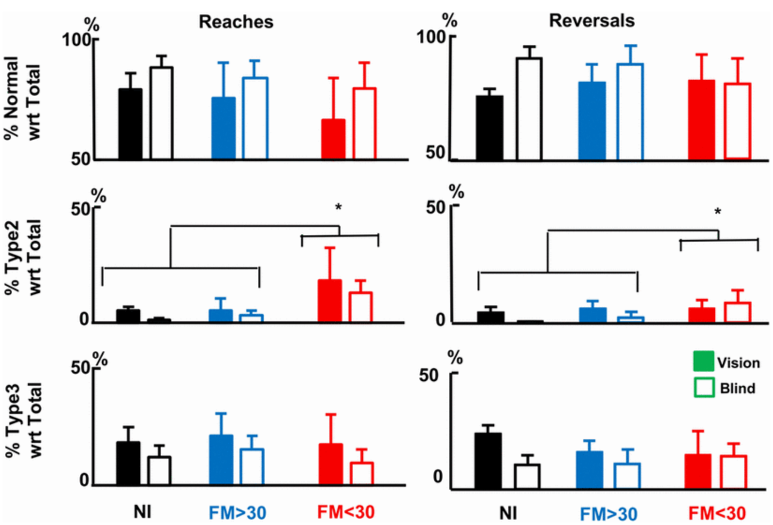

Figure 3. Submovement incidence by type expressed in percentage of the total number of movements.

Table II Three way anova for type 2 submovement

source	df	F (df, 36)	p
MovType	1	1.59	0.17
Vision	1	1.28	0.26
Impairment	2	4.98	0.012
MovType * Vision	1	0.24	0.62
MovType * Impairment	2	1.18	0.31
Vision * Impairment	3	0.069	0.93
MovType * Impairment* Vision	2	0.31	0.37

SECTION IV.

Discussion

We studied secondary submovements during the trajectory portion of point-to-point reaching movements and the outward phase of out-and-back movements in a group of chronic stroke survivors and age-range-matched neurologically intact individuals. We found that only the SS with severe motor impairment presented a significant increase in the incidence of secondary submovement. We also found that these submovements were type 2 submovements. Though not statistically significant, we observed that type 2 submovements tended to emerge more frequently during point-to-point reaching movements (Fig. 3)

It has been proposed that type 1 (gross) submovements are trajectory irregularities that emerge almost exclusively at the final position (stabilization phase) of reaching movements.[5,6,13] Therefore type 1 submovements should emerge neither during the trajectory portion of the reaches nor during the outward phase of the reversals, which is the portion of the movement included in our analysis, and thus our negative results accord with that interpretation.

Much controversy surrounds the origins of type 2 and 3 (fine) secondary submovements. While some authors have suggested that submovements represent corrective adjustments and result from mechanisms of movement accuracy regulation,[9,13,15] Dounskaia and colleagues[6] challenged that interpretation and proposed instead that type 2 and 3 submovements emerged as a result of velocity fluctuations due to

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slow speed. We observed that within a similar velocity range some movements had secondary submovements (type 2 or type 3) while others did not (Fig. 2 A, B, *C)*. Though movements performed by SS with severe impairment were overall slower than those performed by SS with moderate impairment and NI, our results suggest that other factors than slow speed might contribute to the emergence of type 2 and 3 submovements.

Interestingly, Houk and collaborators in a series of experiments in monkeys,[14] using a step-tracking task in which the target jumped to a different location as movement started, they proposed that submovements could result from adopting the strategy of undershooting the target to issue a discrete correction (a secondary submovement) in the direction of the primary movement. According to these authors, in circumstances of noise or uncertainty, such strategy prevents having to break the movement or change the direction of motion and minimizes total movement time. These authors predicted that "under increased sensory noise [i.e. vision, proprioception] the movement's velocity profile will become more segmented." In our study, type 2 submovements, representing re-accelerations, were significantly increased in the group of SS with severe impairment even though they did not have clinically-identified sensory deficits (visual, tactile, proprioceptive). It is possible that the clinical measures of sensory integrity were not sufficiently sensitive to identify meaningful sensory deficits. It is also possible that motor impairment could be construed as arising from a "noisy" controller. Thus SS with the most severely impaired arms could use such a strategy to improve the spatial accuracy of their trajectories by issuing multiple corrective submovements.

In our study SS with different levels of impairment as measured with the FM scale also presented different levels of spasticity as measured with the MAS scale. Much controversy surrounds the interpretation and measurement of spasticity. A recent study has shown that, in addition to the enhanced reflex response at rest, the spastic-paretic muscle shows impaired rate modulation during voluntary movements that could result from higher levels of proportional inhibition or the disruption of signals coming from the corticospinal tracts.[15] Moreover, it has been shown that SS without sensory deficits might maintain intact their ability to plan the movement while the execution of the movement is strongly affected by altered stiffness and damping values.[16] Therefore, spasticity might also play a role in the emergence of type 2 submovements since SS that had increased incidence of type 2 submovements had also higher MAS scores.

The interpretation of our findings, though limited by our small sample, offers some insight into movement deficits after stroke. We have found significant differences between the movement kinematics of stroke survivors with greater (FM$<$30) and lesser (FM$>$30)

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motor impairment. Notwithstanding the great value of large-scale studies, our results highlight the need to study movement deficits in well-defined groups of stroke survivors spanning different levels of impairment.

References

[1]N. Leibowitz, N. Levy, S. Weingarten, Y. Grinberg, A. Karniel, Y. Sacher, C. Serfaty, N. Soroker, "Automated measurement of proprioception following stroke", *Disability and Rehabilitation*, vol. 30, pp. 1829-1836, 2008.

[2]L.S. Simo, C. Ghez, L. Botzer, R.A. Scheidt, "A Quantitative and standardize robotic method for the evaluation of arm proprioception after stroke", *Conf Proc. IEEE Eng. Med. Biol. Soc. 2011*, pp. 8227-8230.

[3]S. P. Dukelow, T. M. Herter, S. D. Bagg, S. H. Scott, "The independence of deficits in position sense and visually guided reaching following stroke", *J. Neuroeng. Rehabil*, vol. 9, pp. 72-80, 2012.

[4]J. Roh, W.Z. Rymer, E. J. Perreault, S. B. Yoo, R. F. Beer, "Alterations in upper limb muscle synergy structure in chronic stroke survivors", *J. Neurophysiol*, vol. 3, pp. 768-781, 2013.

[5]L. Fradet, G. Lee, N. Dounskaia, "Origins of submovements in movements of elderly adults", *J. Neuroeng. Rehabil*, vol. 5:28, 2008.

[6]N. Dounskaia, L. Fradet, G. Lee, B.C. Leis, C. H. Adler, "Submovements during pointing movements in Parkinson's disease", *Exp. Brain Res.*, vol. 193, pp. 529-544, 2009.

[7]H.I. Krebs, M. L. Aisen, B. T. Volpe, N. Hogan, "Quantization of continuous arm movements in humans with brain injury", *Proc. Nat. Acad. Sci.*, vol. 96, pp. 4645-4649, 1999.

[8]B. Rohrer, S. Fasoli, H. I. Krebs, R. Hughes, B. T. Volpe, W. R. Frontera, J. Stein, N. Hogan, "Movement smoothness changes during stroke recovery", *J. Neurosci.*, vol. 22, pp. 8297-8304, 2002.

[9]J. C. Houk, C. Bastianen, D. Fansler, A. Fishbach, D. Fraser, P. Reber, S. A. Roy, L.S. Simo, "Action selection and refinement in subcortical loops through the basal ganglia and the cerebellum", *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, vol. 362, pp. 1573-1583, 2007.

[10]L. Dipietro, H. I. Krebs, B. T. Volpe, C. Bever, S. T. Mernoff, S. Fasoli, N. Hogan, "Learning not adaptation characterizes stroke motor recovery: Evidence from kinematic changes induced by robot-assisted therapy in trained and untrained task in the same work space", *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 20, pp. 48-57, 2012.

[11]A. Fugl-Meyer, L. Jaasko, I. Leyman, S. Olsson, S. Steglind, "The post-stroke hemiplegic patient. I. A method for evaluation of physical performance", *Scand. J. Rehab. Med.*, vol. 7, pp. 13-31, 1975.

[12]K. M. Zackowski, A. W. Dromerick, S. A. Sahrmann, W. T. Thach, A. J. Bastian, "How do strength sensation spasticity and joint individuation relate to the reaching deficits with chronic hemiparesis?", *Brain*, vol. 127, pp. 1035-1046, 2004.

[13]D. E. Meyer, R. A Abrams, S. Kornblum, C. E. Wright, K. JE Smith, "Optimality in human motor performance: ideal control of rapid aimed movements", *Psychol. Rev.*, vol. 95, pp. 340-370, 1988.

[14]A. Fishbach, S. A. Roy, C. Bastianen, L. E. Miler, J. C. Houk, "Deciding when and how to correct a movement: submovements as a decision making process", *Exp. Brain Res.*, vol. 177, pp. 45-63, 2005.

[15]C. J. Mottram, C.J. Heckman, R.K. Powers, W.Z. Rymer, N. L. Suresh, "Disturbances of motor unit rate modulation are prevalent in muscles of spastic-paretic stroke survivors", *J. Neurophysiol*, Feb 2014.

[16]D. Piovesan, M. Casadio, F. A. Mussa-Ivaldi, P. Morasso, "Comparing two computational mechanisms for explaining functional recovery in robot-therapy of stroke survivors", *Biomedical Robotics and Biomechatronics (BioRob) 2012 4th IEEE RAS & EMBS International Conference on*, pp. 1488-1493, 2012.

2014 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), (2014): 5357-5360. DOI.