Deficits of sensorimotor control and their impact on limb stabilization post-stroke: a case series

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Introduction: Recent experimental evidence finds that within single reaching movements, the brain normally invokes separate control actions to generate the limb's trajectory and its final stabilized posture[1-4]. Other studies suggest the potential for differential impairment in the control of limb trajectory and limb posture post-stroke[5-6]. Here, we sought to characterize stroke-related deficits in the sensorimotor regulation of limb posture. In particular, we sought to determine how stroke-related deficits in proprioception and in neuromuscular coordination impact the ability to stabilize the limb against predictable and unpredictable force perturbations comparable to ones experienced during tasks of daily living.

Methods: Six neurologically-intact (**NI**) subjects and two hemiparetic stroke survivors (**SS**) consented to participate. All subjects completed 2 tasks with a horizontal planar robot (Fig 1a). The first, a stimulus detection task, quantified the magnitude and trial-to-trial variability of the smallest detectable force applied to the hand (Fig. 1b). The purpose of this task was to assess each subject's ability to use proprioception to detect robotic perturbations to be applied in the second task. The second task, limb stabilization, required subjects to maintain their hand at a workspace location specified by a visual target during 4 types of mechanical perturbations (Fig 1e). Performance was evaluated both with and without visual feedback of hand position during the 60 s perturbation intervals. Four perturbation conditions were evaluated: a slow, 0.2 Hz (low-frequency **LF**) force vector that rotated predictably in a counterclockwise manner; a high frequency (**HF**) force vector that "jiggled" unpredictably (a sum of sinusoids at 1.1Hz +1.2 Hz+1.65 Hz+1.75 Hz); a combination of the low and high frequency perturbations (**LF+HF**); and a single, brief (0.3 s) 5N force pulse (**PULSE**) applied unpredictably 20 s to 30 s into the trial in a direction of elbow and shoulder extension. We also collected "blind" baseline trials wherein subjects were not to intervene against perturbation (**RELAX**). Thus there were 12 test conditions; 4 stabilizations with visual feedback, 4 without, and 4 relax conditions. Kinematic performance while stabilizing was quantified using the distance (error) between the target and instantaneous hand location. Shoulder and elbow EMGs were zero-mean rectified and low-pass filtered (20 Hz) before normalization (Figs 1c,d). Muscle pairs were used to obtain two measures of joint coordination: coactivation (**CoA**) defined as the instantaneous minimum of normalized flexor/extensor EMG values, and difference activation (**DiffA**) computed as the instantaneous difference in normalized flexor/extensor activities. Power spectra of CoA and DiffA (Matlab `pmtm`) were compared across groups in each condition to quantify the impact of stroke on the use of visual and proprioceptive feedback to generate coordinated, energy-efficient compensations for the perturbations.

Results: Subject characteristics – Stroke subjects' UE FM scores were 21 & 24/66 and both had impaired proximal and impaired or absent distal UE proprioception as assessed with the "up/down test". The **Stimulus Detection** task quantified proprioceptive deficits on a scale commensurate with limb stabilization against environmental perturbation. As shown for representative NI and SS subjects (Fig 2a), NIs were better at detecting perturbations and had more consistent assessments than SSs (Fig 2b). The mean and variability of NI thresholds were used to estimate the probability of intact proprioception for SSs. Thresholds for both SS were well outside the NI 99.9% CI. **Stabilization, kinematics –** When visual feedback was provided, SSs had markedly more error and variation than NIs (Fig 3a). When visual feedback was removed (Fig 3b), all subjects exhibited a decrement in performance. SS performance nevertheless remained outside the NI 95% CI. **Stabilization, EMG spectra –**EMG activations and coordination patterns (DiffA and CoA) were correlated with imposed force fluctuations, especially during LF perturbation (Fig 4a). DiffA and CoA power spectra confirmed the patterns noted via visual inspection. For both CoA and DiffA, power spectral analysis in the LF condition shows a "task-specific" peak only at 0.2 Hz (Fig 4b, circled data points). These results were consistent across groups (Fig 4c: LF condition data). We accounted for variations in tone by subtracting average power in the 0.5 to 1 Hz range from the power at target frequencies. Compared to SSs, NIs had greater task-specific power in DiffA but not CoA (Fig 4c). Further, power at 0.2 Hz was only large when there was a LF component to the perturbation (Fig 4d). Both SS exhibited an impaired ability to modulate DiffA to compensate predictable LF perturbations. In contrast, they appeared to modulate CoA in a manner similar to NIs.

Conclusions: 1) The stimulus detection task yielded an intuitive quantification of proprioceptive deficits using stimuli suitable for use in the study of limb stabilization. **2)** SS with impaired/absent proprioception exhibited hand stabilization deficits with and without visual feedback. **3)** Vision improved performance in all subjects studied, NIs to a relatively greater extent. **4)** Relative to NIs, both SSs had reduced capacity for coordinated, differential activation of flexors and extensors at the shoulder and elbow, which compromised their ability to compensate for predictable LF force perturbations. In contrast, no reduction of task-specific CoA power was observed in the SS. Nevertheless, elevated noise floors in DiffA and CoA spectra suggest reduced dynamic range of neuromotor control due to elevated muscular tone post-stroke. Future analyses will assess whether task specific patterns of coordinated muscle activities post-stroke are predictive or reactive.

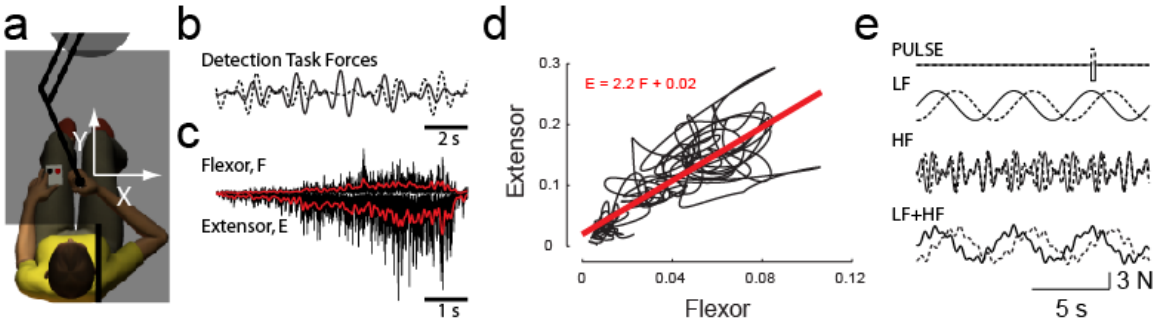

Figure 1: a) Experiment set-up. Subjects sat with arm and hand occluded from view. Subjects held a robot handle. In the stimulus detection task, subjects used a 2-button response box to increase or decrease the force perturbation to be just detectable. **b)** High frequency sum of sines (Fx vs Fy) used in the detection task (4N peak-to-peak max). In alternating trials, subjects either decreased or increased the size of small force perturbations until they could just barely feel motion caused by the imposed forces. **c)** Example EMG raw traces (black) and their low-pass filter envelopes (red) during ramp co-activation while holding hand steady. **d)** For each muscle pair, CoA ramps (as in c) and pulses were used to estimate the relationship between the instantaneous level of activation in each muscle during active maintenance of limb posture. A first-order (linear) fit was used to describe this relationship. The slope of this line was applied as a gain factor to the flexor muscle for computations of CoA and DiffA. **e)** Perturbations used in stabilization task: predictable (LF: low frequency) and unpredictable (HF: high frequency) forces.

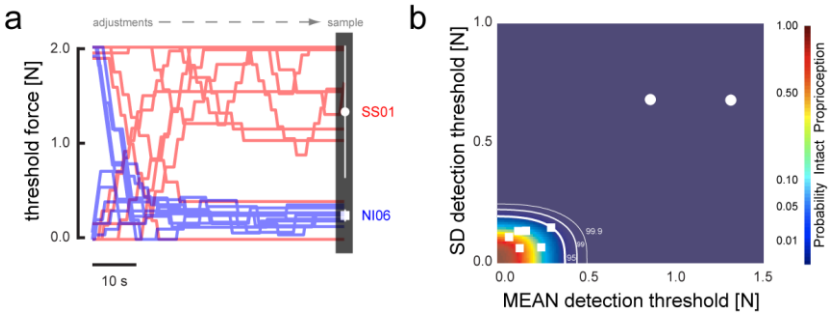

Figure 2: Stimulus Detection. **a)** Sample force adjustment "trajectories" for representative NI (blue) and SS (red) subjects. Each trace depicts the instantaneous mean robotic force over the course of each 60 s trial. Threshold was taken as the force magnitude at the end of the trial. The mean and SD for each subject's evaluations are depicted to the right of the figure. **b)** Normative performance plot showing the relationship between the mean and SD values of detection threshold superimposed on the likelihood of intact proprioception derived from the NI performance. NIs (squares) are clustered in the bottom left corner whereas the SSs (circles) are well outside the 99.9% CI bounds.

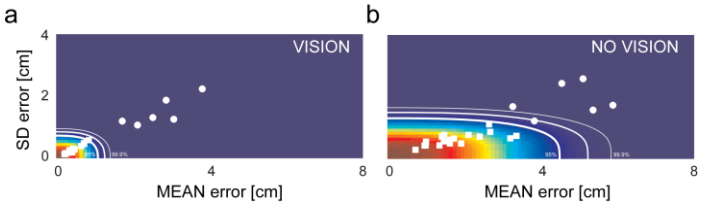

Figure 3: Stabilization – Kinematics. Stabilization error (mean vs. SD) with (**a**) and without (**b**) visual feedback for all 3 sum-of-sines conditions. NIs: squares; SSs: circles. Color scale as in Fig 2b. Both SSs had difficulty stabilizing their limb on target. Performance in both groups was better with ongoing visual feedback than without.

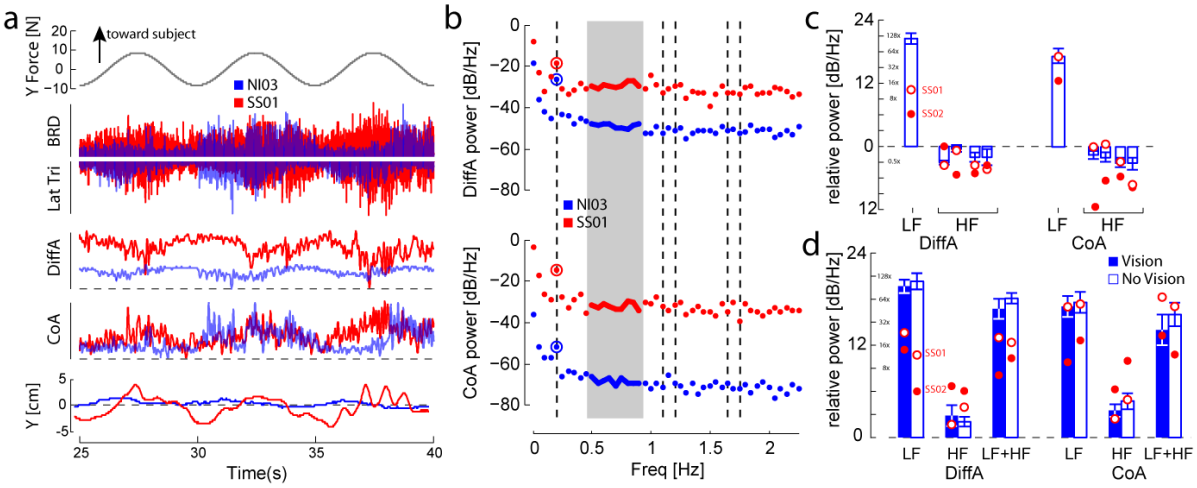

Figure 4: Stabilization – EMG. Data in a-c are from the LF condition with no visual feedback. **a**) Exemplar trial for NI03 (blue) and SS01 (red); top: imposed *Y*-force; 2nd: Brachioradialis and Lateral Triceps EMG activity. Data are 60 Hz filtered and zero mean rectified; 3rd: DiffA; 4th: CoA; bottom: robot *Y*-position centered at the initial position (black dashed line). **b**) Example power density spectra for DiffA (top) and CoA (bottom) for NI03 (blue) and SS01 (red). Data points at the perturbation frequency are circled; there is a task-specific peak in power at this frequency. The section highlighted in gray represents data used to compute baseline. Vertical lines represent all possible frequencies for imposed perturbations. **c**) LF task: Group analysis (mean±SEM) of relative power for the DiffA (left) and CoA (right) signals Circles depict the individual SS data (open for SS01 and filled for SS02). Task-specific power in DiffA at the low frequency is ~10x greater in NIs vs. SS. There is little HF power in this condition. **d**) Task specificity of the relative magnitude of LF (0.2 Hz) power during all 6 active stabilization conditions. Both SSs showed an impaired ability to modulate DiffA to compensate for predictable LF perturbations. They appeared to modulate CoA in a manner similar to NIs.

References Cited:

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