Neural Correlates of Dynamic Adaptation during Wrist Pointing

Andria J. Farrens,[1] Andrea Zonnino,[1] and Fabrizio Sergi[1]

***Abstract*— Our group recently developed a novel fMRI-compatible wrist robot, the MR-SoftWrist, to study the neural correlates of force-field adaptation. Here we present our first fMRI pilot study on four healthy subjects. Our results validate the MR-SoftWrist as a tool for investigating motor adaptation during wrist pointing movements executed during fMRI, and compare neural activations associated with motor control in three different dynamic conditions.**

I. INTRODUCTION

Neuromotor adaptation is a common framework used to study motor learning [1]. While the behavioral effects of motor adaptation have been extensively studied, its neural correlates are much less understood. An understanding of the neural correlates of motor adaptation can be derived using whole-brain imaging techniques such as functional magnetic resonance imaging (fMRI). Task-based fMRI acquired during subject interaction with a novel force field can be used to localize neural activity associated with active motor adaptation processes [3], [4]. Resting state fMRI, acquired pre- and post-motor learning, enables measurement of functional connectivity between brain areas that is reflective of the neural processes responsible for motor memory formation immediately following motor learning [5], [6]. Due to restrictions imposed by MRI compatibility, most previous studies used visuomotor distortions to study motor adaptation [3], with only a few investigating the neural correlates of adaptation in response to dynamic perturbations applied with tools such as robots [4], [12]. Moreover, previous studies that combined robotic devices with neuroimaging used tasks that required shoulder/elbow rotations that introduce potential confounds to fMRI through head movements and movement-induced magnetic field distortion [7], [8].

We have recently developed a novel fMRI-compatible robot, the MR-SoftWrist, that allows application of fMRI to the study of motor adaptation to force perturbations during wrist pointing, a task that can be executed in the MRI scanner without significant image degradation [9]. Here, we present the results of our first fMRI pilot study on four healthy subjects where we establish the neural correlates of motor adaptation to force perturbations and the ensuing formation of motor memories following interaction with the MR-SoftWrist.

*Work supported by the AHA Scientist Development Grant 17SDG33690002, by the University of Delaware Research Foundation grant no. 16A01402, by the ACCEL NIGMS IDeA grant U54-GM104941.

[1] Human Robotics Lab, Department of Biomedical Engineering, University of Delaware, Newark, DE USA. afarrens@udel.edu, zonni@udel.edu, fabs@udel.edu

II. METHODS

A. MR-SoftWrist

The MR-SoftWrist (Fig. 1) supports wrist rotations about two axes, wrist flexion-extension (FE) and radial-ulnar deviation (RUD), in a circular workspace with a radius of 20 deg. The MR-SoftWrist has a maximum output torque of 1.5 N·m, an impedance control bandwidth of 5 Hz, and measures end-effector force, velocity and position at a rate of 100 Hz. We have recently demonstrated the fMRI compatibility of the MR-SoftWrist [10]. Force control in the MR-SoftWrist is obtained using piezoelectric ultrasonic motors and compliant force feedback provided by phosphor bronze springs placed in series with the robot legs. For an in-depth description of its design and control see [11].

B. Experimental protocol

We adapted the standard force-field reaching task [1] to wrist pointing. Subjects held the handle of the MR-SoftWrist with their dominant (right) hand to control a cursor displayed on a monitor that was visible to the subject during fMRI. FE of the wrist moved the cursor horizontally, while RUDs moved the cursor vertically. Subjects were cued to make alternating FE rotations to move the cursor along a straight path to one of two targets, placed at (±15,0) degrees in FE, RUD respectively. Subjects performed wrist pointing under three separate conditions: a no-force (NF) field, a resistive force (RF) field, and a counter-clockwise force field (CF). In the NF mode, the robot was used as a motion tracking system to measure baseline performance with minimal interaction forces. In the RF and CF conditions, the robot applied a velocity-dependent torque, $\tau = B\dot{\theta}$. In these modes, the robot applies torque perturbations $\tau = [\tau_{FE}, \tau_{RUD}]$, proportional to the measured velocity $\dot{\theta} = [\dot{\theta}_{FE}, \dot{\theta}_{RUD}]$. In the RF mode,

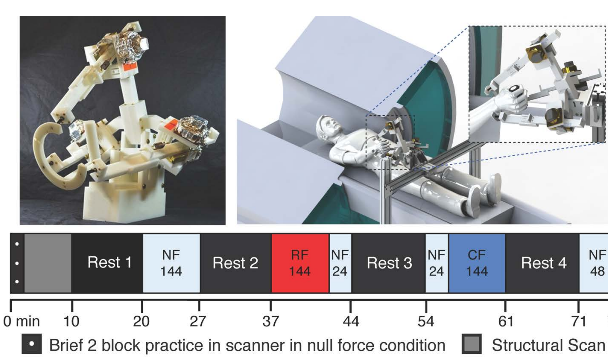

Fig. 1. Top: MR-SoftWrist in its operating condition. Bottom: fMRI task design. Number of trials are listed beneath each active block title.

$B = [-2.5, 0; 0, -2.5]$ mN·m·s/deg, effectively increasing the impedance in the direction of movement. In the CF mode, $B = [0, 2.5; -2.5, 0]$ mN·ms/deg, resulting in lateral perturbations to the direction of movement.

MR images of all patients were acquired with a 3-T Siemens scanner using a 64-channel head coil. Functional images were collected (2 mm isotropic resolution, 1 sec. TR) during both resting and task execution (Fig. 1, Bottom). All three active conditions were executed sequentially, with resting state scans interleaved. Each active condition comprised 6 blocks of 24 trials each, with 15 s. breaks between blocks.

C. Data Analysis

1) Behavioral measures: Subject performance during task execution was quantified via the analysis of movement velocity profiles and trajectory error. For each trial, movement onset was defined as the first time that the velocity of the hand movement exceeded 1 rad/s for 200 ms consecutively in the cued direction [13]. Movement end was defined as the time after peak velocity when the hand velocity dropped below 1 rad/s. This choice excluded any corrective movements at the end of the trial that are not associated with feed-forward motor adaptation.

Consistent with previous motor adaptation studies, we defined trajectory error as the angle between the position of the cursor at 180 ms after movement onset and the target relative to the starting cursor location [13]. Counter-clockwise aiming errors were defined as positive. Single-subject one-way repeated measures ANOVA were run to assess the effects of control mode (NF, RF, CF) on trajectory error. The presence of after effects was quantified by a t-test between trajectory error measured in the NF block following the CF mode and the final block of the initial NF mode.

2) fMRI data: fMRI data were preprocessed using the standard SPM preprocessing pipeline: realignment, segmentation and normalization into MNI space for group analysis. We used a simple block design to investigate the effect of each active condition (NF, RF, and CF) on neural activity, and included head motion parameters as regressors of no interest. Head movement for all subjects was confirmed to be less than 1 mm. To investigate the neural activity associated with adaptation to the lateral force field, we preformed contrasts between conditions CF and NF. The contrast between the CF and RF served as a secondary control for neural activity associated with force. Analysis of resting state data is pending.

III. RESULTS

A. Behavioral measures

Analysis of trajectory error showed characteristic effects of motor adaptation, which included decreased trajectory error in the CF block, as well as after effects in the subsequent no-force condition that follow an exponential trend (Fig. 2). The one-way ANOVA shows a significant effect of CF mode on trajectory error ($p < 0.001$ for all subjects), with errors progressively increasing in the NF, RF, and CF mode respectively ($e_{RF} = 0.11 \pm 0.11$ deg, $e_{NF} = 0.34 \pm 0.97$ deg, $e_{CF} = 8.77 \pm 2.52$ deg). Pairwise comparison of error in the NF block following training in the CF condition showed significant increase in trajectory error in the opposite direction, indicative of after-effects ($p < 0.001, e_{postCF} = -5.67 \pm 3.38$ deg).

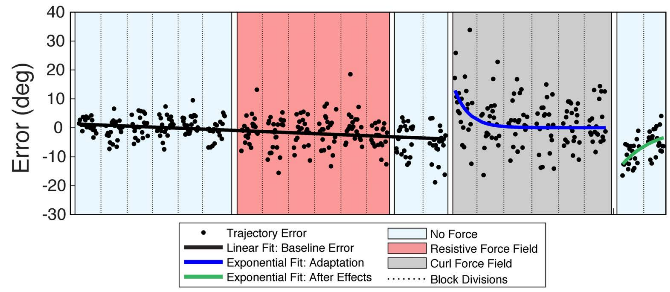

Fig. 2. Trajectory error in all active conditions for a representative subject.

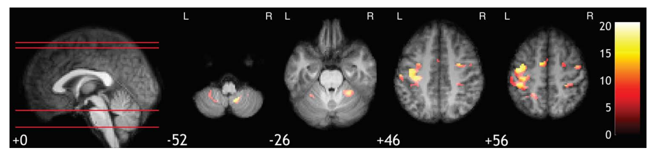

Fig. 3. Axial sections of positive CF-NF contrast map ($p_{FWE} < 0.05$)

B. fMRI Analysis

During the NF, RF, and CF conditions, activations were localized predominantly in the left motor cortex, left parietal cortex, left thalamus and right cerebellum V, and VIII, in line with current knowledge on motor control. For our specific paradigm, however, bilateral activation was detected in the motor and parietal cortex, as well as in the cerebellum. The contrast between CF and NF conditions highlights that the CF mode elicits a greater activation in both the left and the right primary motor cortex, as well as in the right and the left cerebellum V and VIII, suggesting that greater involvement of bilateral motor areas is used for task execution under lateral perturbations (Fig. 3). The contrast between CF and RF conditions, which is meant to isolate the effects of adaptation under matched force conditions, shows greater activity in the right motor cortex and the left cerebellum, which suggests a greater involvement of the non-dominant cortico-cerebellar pathway for lateral perturbations as opposed to resistive forces.

REFERENCES

[1] R. Shadmehr et al., J. Neurosci. 14:32083224, 1994
[2] J. Diedrichsen et al., J. Neurosci., 25(43):9919-9931, 2005
[3] S. Kim et al., PLoS Biol, 13(12):1-23, 2015
[4] J. Diedrichsen et al., J. Neurosci, 25:99199931, 2005
[5] N. Albert et al., Curr Biol 19(12):1023-1027, 2009
[6] S. Sami et al., J. Neurosci, 34(11):3982-3992, 2014
[7] J. Diedrichsen et al., Neuroimage, 27(3): 624-634, 2005.
[8] T. Lemmin et al., J. Neurosci. Meth., 192(1): 58-69, 2010.
[9] L. Shmuelof et al., J. Neurophys, 112(4): 971-980, 2014
[10] A. Farrens et al., IEEE Trans Biomed Eng., PP(99):1-12, 2017
[11] A. Erwin et al., IEEE Trans Neural Syst Rehabil Eng., 25(9):1489-1499, 2016
[12] H. Krebs et al., Hum Brain Mapp., 6(1):7587, 1998
[13] Y. Tseng et al., J Neurophysiol., 98:5462, 2007