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Laura Marchal-Crespo, Lukas Jäger, Christoph Hollnagel, Mike Brügger, Heike Vallery, Robert Riener
Sensory-Motor Systems Lab, Department of Mechanical and Process Engineering, ETH Zurich, Switzerland and University Hospital Balgrist,Medical Faculty, University of Zurich, Switzerland
E-Mail: laura.marchal@mavt.ethz.ch

Heike Vallery
Biomedical Engineering Department, Khalifa University of Science, Technology and Research, Abu Dhabi, UAE

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Locomotor adaptation: An fMRI pilot experiment

Laura Marchal-Crespo[1], Lukas Jäger[1], Christoph Hollnagel[1], Mike Brügger[1], Heike Vallery[1,2], and Robert Riener[1]

[1] Sensory-Motor Systems Lab, Department of Mechanical and Process Engineering, ETH Zurich, Switzerland and University Hospital Balgrist, Medical Faculty, University of Zurich, Switzerland
[2] Biomedical Engineering Department, Khalifa University of Science, Technology and Research, Abu Dhabi, UAE
Contact: laura.marchal@mavt.ethz.ch

Introduction

Although haptic guidance is often used to facilitate motor training, there is currently little evidence that haptic guidance is more beneficial for learning than unassisted practice [1]. In fact, research on motor learning has emphasized that errors are a fundamental neural signal that drives motor adaptation [2-3]. Evaluation of brain regions involved in adaptation under different robotic training strategies that reduce or amplify errors could provide valuable information on observed behavioral outcomes related to adaptation processes. Here, we present four different control strategies to study the brain regions involved in locomotor adaptation while performing functional Magnetic Resonance Imaging (fMRI): in passive mode (i.e. with haptic guidance), in active mode (i.e. no haptic guidance), with error amplification (i.e. repulsive forces proportional to errors), and in force disturbance mode (i.e with a randomly varying force disturbance). We present the brain imaging results from a healthy subject who stepped in an fMRI compatible robotic walking device while training with the four different control strategies.

Methods

MARCOS

MARCOS is a one-degree-of-freedom robot that can provide active (subject-driven) and passive (robot-driven) gait-like movements during fMRI. MARCOS is pneumatically actuated by two cylinders per leg (Fig. 1), attached to the subject through a knee orthosis and to the foot. The reaction forces between the subject and the robot are measured through force sensors located in the knee attachments and the foot plates (Fig.1). The gait pattern enforced by MARCOS is controlled mainly by the knee cylinder, while the foot cylinder can generate a foot load on the foot sole to emulate ground reaction forces.

Training Strategies

1) Passive mode: the robot guides the gait pattern, while the subject remains passive. The control strategy combines a feedback position controller in parallel with an iterative learning feedforward controller (ILC). The feedback controller generates an actuator input that is proportional to the instantaneous difference between the desired knee position and the measured position. The ILC generates an additional feedforward actuator input trajectory for the current cycle based on the error trajectory of the previous cycles, as described in [4].

2) Active mode: the subject is in charge of the movement generation, while the robot follows the subject movements. Although pneumatic actuation is by definition very compliant, the effect of friction in the cylinders is noticeable. Minimizing the interaction forces between the subject and robot is important in order to allow the subjects to perform the task by themselves, without being disturbed by undesired robot-dynamics. The control strategy for the active mode is a zero force controller on the knee (through the control variable u_{knee}). The nonlinearities due to the different chamber sizes in the cylinder are reduced adding the term $P_2 x$ in equation (1), where x is the position of the knee piston. The weight W of the knee orthosis (8 N) is subtracted from the measured force F_{meas}.

$$u_{knee} = -(P_1 + \mathrm{P}_2 \mathrm{x})(F_{meas} - \mathrm{W}) \qquad (1)$$

Fig. 1: The fMRI compatible robotic stepping actuator MARCOS in the 1.5T MR scanner.

3) Error amplification mode: the controller amplifies the errors generated by the subject when trying to follow a desired knee movement. The controller output is proportional to the difference between the desired knee position and the measured position (similar to a position control), but with a negative gain (K_{amp}=-2 N/m). The error amplification mode has the effect of increasing the overall mean absolute tracking error and the error standard deviation. The error amplification controller is combined with the active mode force control scheme.

$$u_{knee} = -(P_1 + \mathrm{P}_2 \mathrm{x})(F_{meas} - \mathrm{W}) - \mathrm{K}_{amp}(\mathrm{x}_{des} - \mathrm{x}_{meas}) \qquad (2)$$

4) Noise force disturbance mode: this controller produces a sudden jerk in the movement that increases the error standard deviation, but not the overall tracking error. The knee cylinder applies the disturbance as random force pulses with duration of 0.1 seconds each, which occur every 0.5 seconds. The force magnitude is uniformly randomly generated and ranges between ±100 N. The noise disturbance is also added to the zero force controller.

$$u_{knee} = -(P_1 + P_2 x)(F_{meas} - W) + F_{dist}(t) \quad (3)$$

Study Design

A pilot study with one healthy subject was performed in the MR-Center of University of Zurich and ETH Zurich, on a Philips Achieva 1.5T MR system. The experiment consisted of testing the effect of four different training conditions on the brain activation: 1) *Passive:* both legs in passive mode, 2) *Syncro:* right leg in passive mode/left leg in active mode, 3) *Error Amplification (EA):* right leg in passive mode/left leg in error amplification mode, 4) *Noise:* right leg in passive mode/left leg in force disturbance mode. The first condition to be tested was the passive mode in order to allow the subject to understand the task to be performed, while the other three conditions were tested in random order.

The subject was instructed to leave his right leg passive and was requested to actively move his left leg trying to synchronize the legs to achieve a gait-like alternating movement with same amplitude (0.09m) and frequency (0.5Hz). During the first condition, the subject was instructed to keep both legs passive.

Each condition consisted of 40 trials. Each trial consisted of 9 seconds of moving the legs as instructed, followed by a rest phase (5s). Between conditions, the subject was instructed to perform as in the Syncro condition during 100s, to test for re-adaptation.

Results

The active training conditions (syncro, EA, noise) elicited significant activity in the primary sensorimotor networks, bilateral premotor areas and cerebellum (Fig.2 a). A conjunction analysis of the active conditions showed significant activation in the supplementary motor cortex. The passive training condition elicited clusters of significant bilateral activation in frontal and subcortical areas as well as the temporal lobe (Fig. 2 a). A conjunction analysis of all training conditions did not reveal any significant overlapping activity.

Of remark is the fact that activation of the sensorimotor cortex in the active conditions was mainly bilateral, even if the tasks to be performed required only activation of the left leg. Indeed, we observed an increase in the reaction forces between the passive leg and the knee cylinder. This indicates that the subject actively tried to synchronize the passive leg with respect to the active leg when some kind of disturbance was applied to the active knee.

The re-adaptation task after each training condition did not elicit any coincident brain activation across conditions. Analysis of the re-adaptation task after the active conditions (syncro, EA, noise) shows coincident activation in the right primary motor cortex. Globally, there is significant bilateral activation in the primary sensorimotor areas (Fig. 2 b). There is also a trend towards higher involvement of premotor areas the more difficult the preceding training task was (syncro < noise < EA). Re-adaptation after the passive condition elicited significant bilateral activation in the somatosensory association cortex of the superior parietal lobe and the medial cingulate cortex.

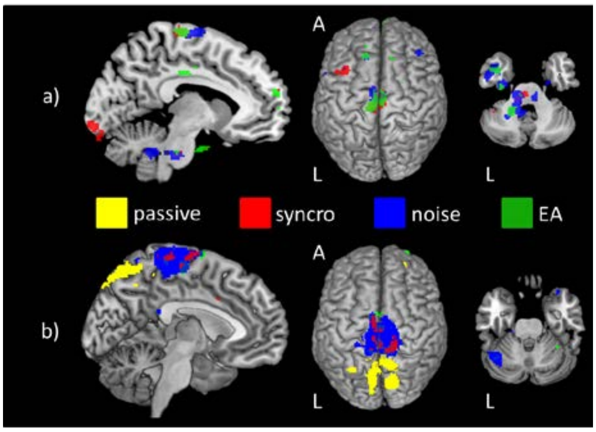

Fig. 2: Brain responses to four conditions (yellow: passive, red: syncro, blue: noise, green: error amplification) a) during training and, b) during re-adaptation. (p=0.05, FWE, min. cluster size 10 Voxels)

Conclusion

With the indispensable reluctance to conclude based on a single subject analysis, all active conditions required a similar cortical network to fulfill the task, while the passive condition solicited activation in different brain areas. We observed a tendency towards more activity in the motor/sensory network the more “challenged” the subject was. We also found that activation of the sensorimotor cortex in the active conditions was mainly bilateral, even if the tasks to be performed required only activation of the left leg and the subject was instructed to maintain that leg passive.

The most interesting result concerns the differences in brain activation during the re-adaptation movements. Even if the solicited movement was the same after each training session, the preceding form of training influenced considerably which brain areas were activated, showing no coincident areas across strategies.

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