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The effects of robotic assistance on upper limb spatial muscle synergies in healthy people during planar upper-limb training

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This protocol adopts a standard paradigm for upper-limb rehabilitation (a planar device with assistive control) with standard linear and challenging curvilinear trajectories to investigate the effect of the assistance in human-robot interaction in healthy people. Ten healthy subjects are instructed to perform a large set of radial and curvilinear movements in two interaction modes: 1) free movement (subjects hold the robot handle with no assistance) and 2) assisted movement (with a force tunnel assistance paradigm). Kinematics and EMGs from representative upper-limb muscles are recorded to extract phasic muscle synergies. The free and assisted interaction modes are then compared assessing the level of assistance, error, and muscle synergy comparison between the two interaction modes.

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Assistive Planar Robot (PLANarm2 prototype available at the UOS STIIMA Lecco laboratories and equipped with position control for preliminary adaptation, admittance control for minimization of forces without providing any assistance and tunnel control over the given planar trajectory to provide normal assistance). A detailed description of the robot can be found at https://www.mdpi.com/2218-6581/9/4/104.

Optoelectronic Vicon (Oxford UK) 10 TVC System (Subjects wear a set of eleven markers, positioned on T8 and C7 vertebras, jugular notch, xiphoid process, greater tubercle, medial and lateral humeral epicondyles, styloid process of the ulna and the radial, second and fifth metacarpal heads. Six markers are placed also on the robot to track the movement, three of these positioned on the base to represent the reference axes; one on the top of the right driven pulley; one on the right joint and the last one on the end-effector).

Subjects are also instrumented with 16 wireless s-EMG probes (Cometa, Milan, Italy) positioned on the following muscles: Erector Spinae (ES), Middle Trapezius (MT), Upper Trapezius (UT), Infraspinatus (IF), Deltoid Anterior (DA), Deltoid Middle (DM), Deltoid Posterior (DP), Pectoralis (PC), Triceps Long Head (TLo), Triceps Lateral Head (TLa), Biceps Long Head (BCl), Biceps Short Head (BCs), Brachioradialis (BR), Pronator Teres (PT), Wrist Flexors (WF) and Wrist Extensors (WE).

As for all robotic operators, during the trials the researcher should be ready to act on the emergency button if any emergency situation should occur.

Setup and subject preparation 30m

1 Calibration of the Vicon system and setup of the Planar Assistive Robot. The robotic setup is placed at the center fo the field of view of the Vicon system, mounted on a standard table and equipped with chairs for both the subject and the researcher, a display to show the requested trajectory and an emergency button for safety reasons. Both the subject and the researcher wear an FFP2 mask and the device is hygenized before the experimental session. 10m

2 The subject wears a set of eleven markers, positioned on T8 and C7 vertebras, jugular notch, xiphoid process, greater tubercle, medial and lateral humeral epicondyles, styloid process of the ulna and the radial, second and fifth metacarpal heads. Six markers are placed also on the robot to track the movement, three of these positioned on the base to represent the reference axes; one on the top of the right driven pulley; one on the right joint and the last one on the end-effector. 10m

3 Subject wears 16 s-EMG electrodes positioned on the following muscles: Erector Spinae (ES), Middle Trapezius (MT), Upper Trapezius (UT), Infraspinatus (IF), Deltoid Anterior (DA), Deltoid Middle (DM), Deltoid Posterior (DP), Pectoralis (PC), Triceps Long Head (TLo), Triceps Lateral Head (TLa), Biceps Long Head (BCl), Biceps Short Head (BCs), Brachioradialis (BR), Pronator Teres (PT), Wrist Flexors (WF) and Wrist Extensors (WE). 10m

Task description

4 The movement targets are oriented toward the main cardinal directions (NE, E, SE, S, SW, W, NW, N) in a circumference with a radius of 170 mm. Using said targets, two types of motion, called Radial and Curvilinear, are considered.

4.1 Description of the Radial task: the Radial movement begins with the hand in the center of each target set and consists in going towards each of the peripheral targets and then coming back to center target (O-NE, NE-O, O-E, …). Each acquisition trial is composed of 16 movements (reaching 8 targets and coming back). After each movement, the subject has to wait for about one second before proceeding to the next target. Subjects are required to move slightly fast, in order to enhance the EMG related to phasic (dynamic) EMG activity. Following this instruction, subjects are expected to complete the Radial exercise in no more than 40-45 s. However, tolerance in execution time is accepted. To prevent fatigue, a 30-second pause is introduced after each trial if the subject needs it. The Curvilinear exercise is repeated 10 times.

4.2 Description of the Curvilinear task: the Curvilinear movement uses the targets as the beginning and end of the curvilinear trajectories, and as way-points. Subjects perform alternately ¼ circle and ½ circle, first clockwise and then anticlockwise (e.g.: from south to west, passing through south-west: S-SW-W; from west to east, passing through north: W-N-E; ...). Following this instruction, subjects are expected to complete the Curvilinear exercise in no more than 50-55 s. However, tolerance in execution time is accepted. To prevent fatigue, a 30-second pause is introduced after each trial if the subject needs it. The

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Curvilinear exercise is repeated 10 times.

Acquisition protocol 1h

5 Both the subject and the researcher sit down where the robotic setup has been placed and the preliminary adaption phase, called "Reference" codition, begins. During preliminary adaptation, the robot is moved with a position controller from target to target with a rectilinear or curvilinear path and trapezoidal-shaped biomimetic velocity profile. Each subject is asked to follow the robot without pushing nor being pushed, thus keeping interaction forces as low as possible.

5.1 The first Reference acquisition is performed following the Radial movements. 10m

5.2 The second Reference acquisition is performed following the Curvilinear movements. 10m

6 The first experimental condition, called "Free", is performed using the admittance controller paradigm. This controller aims to increase at maximum robot compliance, resulting transparent to the user. Each subject has to reproduce the trajectories performed in the Reference condition without any assistance. Participants are asked to reproduce exactly the trajectories shown on screen. During the movement, the display shows the starting point, the end point, the ideal spatial profile and the trajectory carried out by the subject.

6.1 The first Free acquisition is performed following the Radial movements. 10m

6.2 The second Free acquisition is performed following the Curvilinear movements. 10m

7 The second experimental condition, called "Assisted", is performed using the tunnel controller paradigm. This controller has knowledge of the trajectory to be carried out and aims to be transparent to the user in the tangential direction, while a corrective force is produced in the normal direction if the boundaries of a so-called tunnel are surpassed. Each subject has to move the end-effector of the robot with an assistance tunnel built around the given trajectory with a10 mm width.

7.1 The first Assisted acquisition is performed following the Radial movements. 10m

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7.2 The second Assisted acquisition is performed following the Curvilinear movements. 10m

Study timeline and subject recruitment 10w

8 One subject per week is recruited, for ten weeks (ten healthy subjects in total).

Data analysis 10w

9 Kinematics, assistance force and EMG data is aligned, filtered and segmented into sub-tasks. Onset and offset of each movement are computed.

10 Tonic components are removed from EMG envelopes to achieve phasic EMG, and each channel is normalized to the maximum EMG found in all trials for that channel.

11 Spatial synergies and temporal coefficients are extracted for each of the conditions separately (Radial, Curvilinear ½ and Curvilinear ¼) with the NMF algorithm.

12 The analysis of human-robot interaction is conducted by comparing spatial synergies and matched temporal coefficients of the Free and Assisted modes, for each exercise separately, with an intra-subject and inter-subject analysis.

12.1 In the “Assisted” trials, the amount of assistance provided with the robot is computed. Assistance is calculated as the fraction between the summation of the time instants in which the robot force is greater than 0, and the summation of these and of the moments in which the force is equal to 0.

12.2 In each repetition, and for each subject and each direction of motion, the kinematic error values are computed. This is repeated for all directions.

12.3 Kinematic recordings are used to separate movement phases. The segmentation is achieved by computing the velocity profile associated with the marker of the second metacarpal head of the dominant limb and used as signal for detecting movement onsets and offsets. Then, all the movements are aligned by considering the EMGs with 0.25s before the task onset and 0.25s after the respective offset [-0.25s; +0.25s]. The data from 16 sEMG channels are filtered to extract the EMG envelope. Afterwards, the EMG envelopes are further analyzed to extract the phasic component of the EMG,

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removing the postural (tonic) EMG activity from the original signal. In order to perform the non-negative matrix factorization (NMF), negative phasic EMG values are set to zero before synergy extraction. Since Maximum Voluntary Contraction (MVC) is very hardly measured on some muscles, the normalization of the data is performed on the maximum value achieved for each muscle in the complete dataset ("Global Normalization"). Then, synergies (time-invariant spatial loads W) and temporal coefficients (C) are extracted using NMF algorithm. For each subject, the extracted spatial synergies in Free and Assisted conditions are matched by similarity so that each synergy is coupled with the more similar one found in the respective dataset. Then, each couple of matched synergies is assigned a similarity score (cosine product). This analysis is repeated for both the Radial and Curvilinear exercises.

Outcome measures and statistics

13 As outcome measures, the following is considered:

- Temporal percentage of assistance force
- Kinematic Error
- Spatial Synergies
- Temporal Coefficients

14 We hereby summarize the statistical analysis for this study. Throughout the analyses, we analyzed 3 factors: Directions (comparing e.g. O-NE, O-E,… in the Radial case and all the different ¼ circle and ½ circle in the Curvilinear one); Modes (comparing Free and Assisted mode); Exercises (comparing Radial and Curvilinear (¼ circle and ½ circle) exercises). In all conditions, normality of the data was tested with the Shapiro-Wilk test, Matlab swft function. Since many distributions were not normal, the non-parametric Kruskal-Wallis Test was used.

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