Appendix B – Extended Methods

Interventions

Possible phantom movement for upper limb amputees are hand open and close, pronation and supination, wrist flexion and extension, elbow flexion and extension, flexion and extension of the individual fingers. Possible movements for lower limb amputees are knee extension and flexion, femoral rotation outwards and inwards, ankle plantar flexion and dorsiflexion, tibial rotation outwards and inwards, ankle eversion and inversion, flexion and extension of the toes. Upper and lower limb movements can be performed individually and simultaneously (more than two movements at the same time). Depending on the level of amputation, some movements are omitted from the treatment because they involve the residual rather than the phantom limb: e.g. elbow movements in transradial amputees. According to whether the subjects are assigned to the control or experimental intervention, they are asked to either imagine or execute these phantom movements as naturally and intuitively as possible.

Experimental Treatment

A Phantom Motor Execution (PME) treatment session consists of the following components:

1. **Placement of electrodes and fiducial marker.** To place the electrode in an appropriate way, subjects are asked to execute different phantom movements while the stump is palpated to localize the muscles. Areas with excess of soft-tissue between muscles and skin are avoided. Four to eight bipolar superficial electrodes (pre-gelled, adhesive, Ag/AgCl, one cm diameter, and two cm inter-electrode distance) are then placed along the muscle fibres where possible, else one electrode is placed on the target muscle while the other is placed on a more electrically neutral area. In the case of transfemoral amputations, electrodes are placed according to the *targeted monopolar configuration* described in detail in reference: (Lendaro et al., 2017).

2. **PME training cycle** (see Figure B1)
   a. **Recording session.** The subjects are asked to perform three repetitions of the movements as shown by a virtual limb alternated by rest periods. The standard contraction time is set to three seconds followed by three seconds of relaxation. However, this time might be increased in case longer time is required to complete the phantom movement. This step is necessary to collect myoelectric data used to train the motor volition decoding algorithms. The movements performed are dictated by the current level of difficulty (see "Levels of difficulty").
   b. **Phantom motor execution in augmented reality (AR).** The subjects are then asked to control the virtual limb by performing the movements previously trained.
   c. **Serious gaming.** Each phantom movement trained during the recording session is then paired to activate a specific key on the computer keyboard. Computer games that would normally be controlled by those keys can then be controlled by the phantom movements, enabling the control of the game through *phantom motor execution*.
   d. **Target achievement control (TAC) test.** In this part of the training cycle the subjects are asked to move a virtual limb aiming to match a target posture determined by the movements previously trained. The target posture is considered achieved when the subject is able to position the virtual limb within ±5 degrees range in less than 20 seconds, and hold it for a two-second dwell interval. The trained movements are randomly requested six times each. This test was originally designed to evaluate control strategies for multi-functional prosthetic devices represented in virtual reality (Simon et al., 2011) In this study, the TAC test is used only for rehabilitation purposes and it is used as implemented in our open source platform named BioPatRec (Ortiz-Catalan et al., 2013).

3. **Outcomes evaluation.** Depending on the specific visit different outcome measures are recorded by blind evaluators at the end of the treatment, as reported in Table 2.
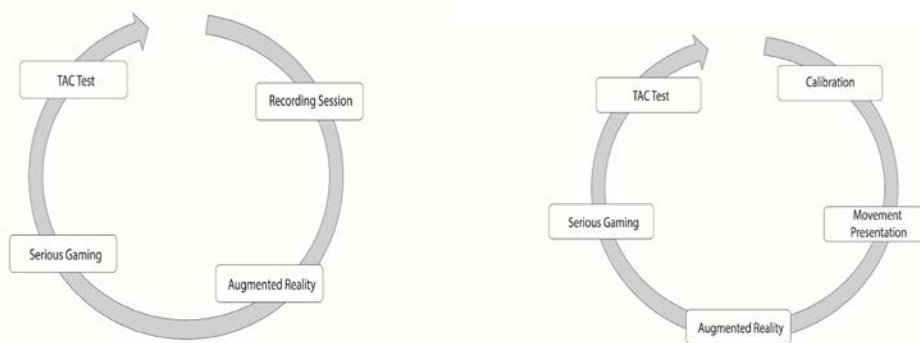

Figure B1: Training cycle for the Phantom Motor Execution (PME) intervention (left) and Phantom Motor Imagery (PMI) intervention(right)

Control Treatment

A Phantom Motor Imagery (PMI) treatment session consists of the same components as the experimental intervention, however there are some differences in the treatment cycle (see Figure B1), which are listed below:

- **Calibration.** The training cycle starts with the calibration. During this step, the patient is asked to relax the muscles completely and stay still. This phase is required in order to set the relaxation or "non-activity" level and enable the detection of contractions associated with unwanted motor execution.
- **Movement presentation.** This step is the analogue of the recording session in the experimental treatment and is meant to present a sequence of selected movements to the subject. The movements are chosen based on an increasing level of difficulty (see "Levels of difficulty"). Every movement is presented three times, for a period of three seconds in each repetition, and alternated by rest periods of equal length. During this phase the subject is asked to practice the imagination of the movements.
- **Serious gaming.** In the gaming step, the subjects will control the game using the keyboard with an able limb. No imagination is required for this step. However, the patient is expected to engage in an entertaining activity and divert cognitive resources that would be otherwise devoted to pain processing. Bilateral upper limb amputees will use a joystick with any able limb.
- **Phantom motor execution in augmented reality (AR) and TAC test.** The subjects are asked to imagine being in control of the movements autonomously performed by the virtual limb in both AR and VR environments.

Levels of difficulty

Interventions can be performed at five levels of difficulty. Subjects start at the easiest level and advance to the next level following different modalities depending on their intervention group. Subjects assigned to the PME group move to the next level when they achieve 85%-100% completion rate in the TAC test. If subjects are unable to achieve over 30% of completion rate in the new level, they are advised to move back to the previous level. On the other hand, subjects assigned to the PMI group are instructed on the specific amount of time to spend in each level, which increases with the number of degrees of freedom (DoF) exercised within the same treatment cycle.

- Level 1: Individual movements (1 DoF).

- Level 2: Individual movements (2 DoF). In the second level more than two movements are requested within the same training cycle while keeping each movement independent.
- Level 3: Simultaneous movements (2 DoF). Subjects are required to combine more than one DoF, i.e. pronation while opening or closing the hand, or supination while opening or closing the hand.
- Level 4: Individual movements (3 DoF).
- Level 5: Simultaneous movements (3 DoF).