Complex Motor Cortex Control of Muscle Synergies Underpin Simple Reaching Tasks in Robot-Induced Force Fields

Duncan L. Turner, Paul Sacco, Timothy Hunter

Rehabilitation Centre, School of Health and Biosciences, University of East London, London E15 4LZ, England (e-mail: d.l.turner@uel.ac.uk)

Abstract: In order to design effective human-machine interfaces, it is important to demonstrate that stereotypical movements such as reaching display predictable patterns of activation in muscles that operate at shoulder, elbow and wrist joints. Whilst humans display a wide repertoire of adaptive behavior in natural movements, this study demonstrates that muscles acting at different arm joints operate in synergies during reaching movements in a direction-dependent manner. These basic synergies can be mapped to similar direction-dependent motor cortex excitability maps and this plasticity of muscle and central nervous system should be taken into account when developing actuator systems which mimic natural movement.

1. INTRODUCTION

Several studies have demonstrated that a relatively simple movement such as reaching, as well as a complex behaviour such as forward walking, both engage patterns of activation in many muscles. The activation patterns can be constructed using a smaller number of muscle synergy relationships. For example, an individual's muscle activation pattern across 32 limb and trunk muscles during forward walking can be produced reliably by only 5 muscle groupings or synergies (Cappellini et al., 2006). In fast reaching movements in different directions, it is possible to extract 4 or 5 muscle synergies (from 19 muscle activations) that account for up to 82% of the variation in collated data (d'Avella et al., 2006). However, humans exhibit a remarkable ability to adapt movements to changes in physical conditions and in order to compensate for chronic disease such as stroke (Dipietro et al., 2007). Recently, peripheral muscle synergies have also been mapped to motoneuron pools in the spinal cord during human walking (Ivanenko et al., 2006). This intermediate step in mapping muscle and central nervous system representations of locomotion compliments the large data base illustrating a refined somatotopic representation of arm muscles in the motor cortex of primates and humans (e.g. Alkadhi et al, 2002; Colebatch et al., 1991). In this study, we directly measured muscle activation patterns during arm reaching in robot-induced force fields to illustrate direction-dependent muscle synergy behaviour with an assistive technology employed in stroke rehabilitation. Further, by using transcranial magnetic stimulation (TMS) we provide preliminary evidence that the motor cortex is involved in controlling the pattern of muscle activation, also in a direction-dependent fashion. The results have implications for the use of brain stimulation as an adjunct to robot-induced movement in patients who are unable to fully activate the appropriate muscle synergies such as following a stroke or spinal cord injury.

2. METHODS

2.1 Muscle Synergy Study.

Ten healthy right-handed subjects (18-45 years) performed planar centre-out reaching movements. Each subject sat in front of an interactive robotic device (InMotion2, IMT, USA) with the right lower arm supported against gravity. They grasped a hand-held joystick with which they moved an onscreen cursor to a series of visual targets. The movement was completed within 1.6 sec and subjects held position for a further 1.6 sec before moving back to the centre holding position. Movement directions were approximately 10 cm from the central hold position towards 8 equally spaced targets (25 mm diameter) arranged around the circumference of a circle. Blocks of 25 trials were performed towards each target in a randomised order for each subject. The movements were made against a damping force (25 N) imposed by the IMT robot to mimic pushing a door or drawer. Surface EMG were measured from biceps (BB), triceps (TB), brachioradialis (BR), anterior deltoid (AD) and posterior deltoid (PD) muscles using pre-amplified electrodes (Biometrics, Gwent, UK). EMG signals were sampled at 1KHz and processed (20Hz high-pass filter and full waved rectified) using a CED 1401 unit and Spike 2 software (CED, Cambridge, UK). Values are mean +/- SEM and significance level was set at $p < 0.05$.

2.2 Motor Cortex Study.

Six healthy right-handed subjects (18-43 years) performed similar centre-out reaching movements to study 1. EMG profiles were collected as before for biceps brachii (BB). In addition, TMS pulses were delivered to the optimal scalp position for motor evoked responses (MEPs) from the BB engaged in movements, using a 9 cm diameter figure-of-8 coil (Magstim 200, Magstim Co., UK), held tangentially to the skull. Test pulses were delivered at 130% of the resting motor threshold that was established prior to the reaching movements. The peak-to-peak amplitude of the MEP was determined from 25 trials in each of the 8 reaching directions and the pulses were delivered at 2 time points after the trigger-to-move target was illuminated (150 ms; i.e. before actual movement and 400 ms; i.e. during the movement). All EMG and MEP data was collected and analysed as before, except MEP data was collected at 5 KHz. Values are mean +/- SEM and significance level was set at $p < 0.05$.

3. RESULTS

3.1. Muscle Synergies Study.

The typical muscle activation pattern of one muscle (BB; Fig. 1) demonstrated that, for a planar movement of similar velocity profile to all directions (centre panel), there is a distinct direction-dependent difference in several spatio-temporal characteristics. For the BB muscle, there is significant direction-dependency for peak EMG amplitude and EMG onset time and duration, but not for baseline (tonic) EMG amplitude.

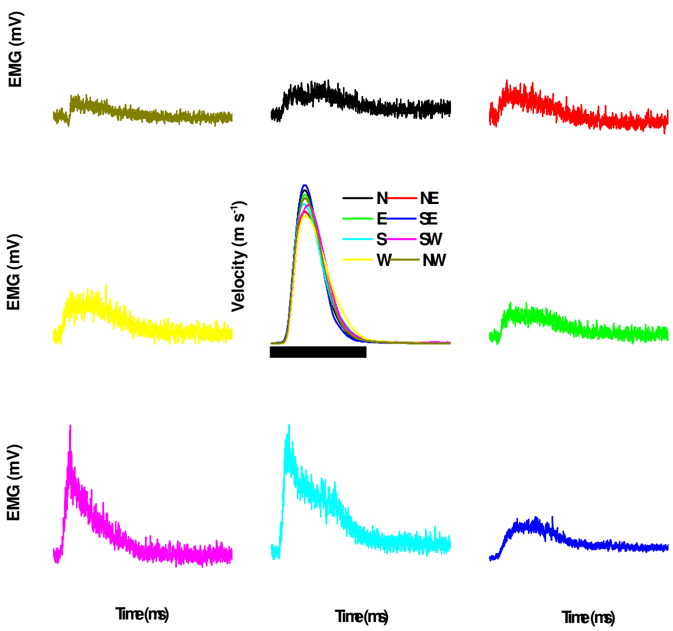

Fig 1. Average (n = 10) rectified EMG profiles for biceps brachii (BB) muscle during reaching in 8 directions in a robot-induced 25N damping force. Movement velocity profile during the movement phase (black bar) is shown in central panel. Each direction is labelled as a geographical direction from a central holding point – that is N is North or away from chest and S is south or towards chest.

Notably in the "preferred" directions for BB activation (South and South-West), the onset for EMG activation is significantly before movement onset time, whereas in non-preferred directions both EMG and movement onset times are similar (Fig. 2). These direction-dependent characteristics were observed in several muscles. A comparison between the 5 muscles studied here show a complex direction-dependent pattern of activation, such that for each direction there is a unique muscle synergy (Fig. 3).

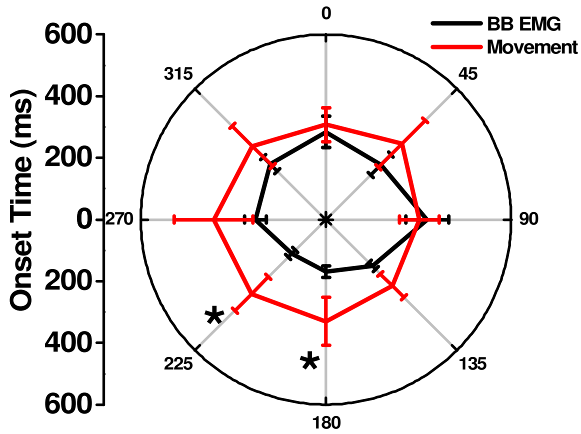

Fig 2. Polar plot showing onset times for BB EMG and movement during reaching to different directions. In the preferred direction for BB activation, EMG onset time (black line) is significantly before movement onset (red line; *, $p < 0.005$). In this plot type, zero degrees represents North direction or away from chest and 180 degrees represents South direction or towards the chest.

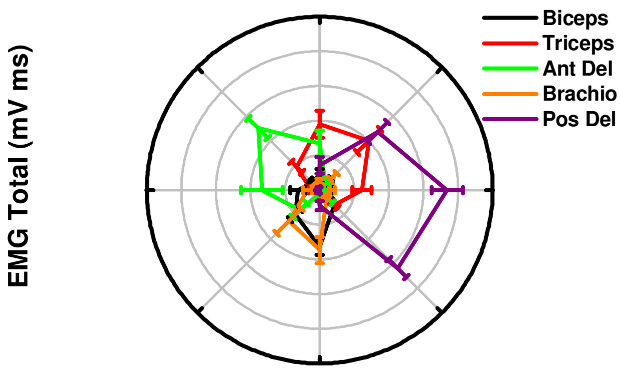

Fig 3. Polar plot for integrated EMG activity [average EMG x EMG duration] for 5 muscles operating across shoulder and elbow during planar reaching movements to 8 directions. Most muscles show some activity in all directions, but all muscles have preferred directions for maximal EMG activity. Synergies exist between muscles, for example BB, brachioradialis and posterior deltoid in a South direction [towards the chest] whereas the anterior deltoid is more involved when moving across to a West direction [across to left].

3.2 Motor Cortex Study

In the second study, TMS pulses were given to the scalp to elicit MEPs in targeted muscles. In this paper, only data of the BB muscle is presented for clarity. There was a marked direction-dependency for BB MEP amplitude. Interestingly, this was for pulses given *both* during movement (400 ms post-move instruction) *and* also before EMG onset (150 ms post-move instruction; fig. 4).

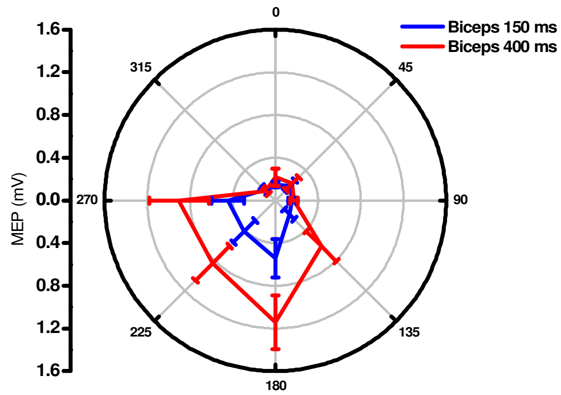

Fig 4. TMS-induced, peak-to-peak MEP amplitude shows direction-dependency in the BB muscle during the preparation (150 ms; blue) and execution of planar reaching movements (400 ms; red) to 8 directions. There was a 25N robot-induced damping force present in all directions.

4. DISCUSSION

Human-machine interfaces are rapidly being developed to aid movement in several types of chronic disease and disability. The main findings from this study are firstly, that a range of muscle activation synergies are available in healthy subjects to enable precise and well timed reaching movements in different directions with robot-induced force fields. We only report data from 5 muscles here, and yet there are clear synergistic activation "signatures" in specific directions. The data from a range of studies of naturalistic behaviours such as reaching in 3D, walking (forwards and backwards) and running suggest that muscle groups can act in a modular fashion, such that whilst several dozen muscles may be active in a behaviour, 4 or 5 synergies can account for most of the variation in movements (Cappellini et al., 2006; d'Avella et al., 2006). We are presently developing such approaches for movement in robot-induced force fields. The interplay between muscles, sometimes calculated by using movement kinematics, is affected by stroke (Dipietro et al., 2007). We predict that this recent finding will be mirrored by subtle changes in the type of activation patterns in individual muscles as shown by direct measurement in Fig 3. For example, more preserved muscles or their compartments may be more active when overall muscle weakness is present and that these relationships will change during recovery of function.

Secondly, this study presents a compelling case for the motor cortex being integral to *planning* a reaching movement as well as in executing the movement itself. Furthermore, we were able to map the excitability (measured by TMS) of the cortex to that of muscle synergy recruitment in a direction-dependent manner. Thus, when there is a direction-dependent loss of function as may occur in stroke and a number of movement disorders, application of therapeutic brain stimulation should be direction-, time- and muscle-specific in order to offer effective action. Several recent studies have documented modest 10-20% improvements in arm function following repetitive brain stimulation post-stroke (reviewed by Talleli and Rothwell, 2007). We suggest here that a more specific spatio-temporal use of brain stimulation may offer a greater added value to robot-induced recovery in stroke.

5. REFERENCES

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