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Research report

Muscular synergies during motor corrections: Investigation of the latencies of muscle activities

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ABSTRACT

To reduce the complexity of muscular control, a small number of muscular activations are combined to produce an infinity of movements. This concept of muscle synergies has been widely investigated, mainly by means of principal component analyses (PCA) in the case of unperturbed movements. However, reaching movements can be altered at any time if the target location is changed during their execution. In this case, PCA does not precisely measure the latencies of muscles activities. We develop here a simple method to investigate how a random target jump toward a single location induced motor corrections in the whole musculature by precisely determining the latencies of muscle activities during a complex pointing movement.

Our main result demonstrated that both initiation times together as well as correction times together were strongly correlated for some pairs of muscles, independently of their occurrences during the motor sequence and independently of the location of the muscles at the anatomical level. This study thus provides a simple method to investigate the latencies of muscular activities and the way they are correlated between certain muscles to stress the muscular synergies involved in the movement. It also suggests that the CNS re-programs a new synergy after the target jumps in order to correct the on-going reaching movement. This latter corrective synergy involves the control of more muscles together compared to that used to initiate the movement. At the level of the Primary Motor Cortice (M1), muscles appear to be controlled as a coupled functional system, rather than individually and separately.

1. Introduction

Considering the large number of muscles that can theoretically be involved in a complex movement, Bernstein [1] suggested that the Central Nervous System (CNS) could simplify the 'problem of redundancy' by grouping the functioning of muscles in more global units. Such a strategy would reduce the number of degrees of freedom that the CNS has to manage. It is now well established that a small number of muscular activations may combine to produce an infinity of movements [2–4]. More specifically, Mussa-Ivaldi and Bizzi [5] and Torres-Oviedo et al. [6] defined muscular synergies as the set of muscles recruited by a single neural command signal, i.e. a set of basic activations that may generate a large repertory of movements. This concept of muscle synergies has been accepted as a CNS strategy used to perform planned movements such as walking, reaching, grasping, pointing and many other motor tasks [2,3,7–10]. This hypothesis has received a great deal of experimental as well as theoretical support ([11,12] for a modeling approach). All of these works have highlighted the use by the CNS of muscular synergies as a strategy to plan complex movements requiring the coordination of many arm, trunk and leg muscles.

Typically, muscular synergies are extracted from the overall EMG activities by using principal component analysis or non-negative matrix factorisation (PCA [13], NNMF [14]). PCA or NNMF are standard statistical techniques generally used to extract a low-dimensional structure from a high-dimensional dataset, by means of a linear technique. Mathematically, the method involves the eigenvalue decomposition of a dataset covariation matrix in order to find the principal directions in high-dimensional space. In the context of muscle synergies, these methods have been used as a dimensionality reduction tool applied to the muscle space. Physiologically, the underlying assumption is that two correlated EMG signals could belong to the same synergy and that, in general, a specific EMG signal could originate from a linear combination of different synergies. Therefore, these covariation analysis allows the

Abbreviations: EMG, electromyography; CoP, center of pressure; A-P, antero-posterior; BRi, brachio radialis; BBi, biceps brachii; TBi, triceps brachii; DAi, deltoïdus anterior; DPi, deltoïdus posterior; PSi, pectoralis superior; LDi, latissimus dorsi; ESi, erector spinae between L3 and L5; RAi, rectus abdominis; BBi, biceps femoris; RFi, rectus femoris of the quadriceps; SOLi, soleus; TAi, tibialis anterior.

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experimenter (i) to find a simpler organization in EMG activities and (ii) to quantify the whole motor strategy in terms of muscles synergies (principal components). Generally, PCAs or NNMF are performed on smoothed (EMG) waveforms which are obtained by using a low-pass filter with a 5 Hz cut-off frequency. However, in this case, the major temporal representation of the EMG data may be lost, given that the 5 Hz low-pass filter is applied to rectified signals which merely represent muscle burst activity that corresponds to the joint angular displacements. As such, PCA or NNMF may not be sensitive enough to detect brief bursts of muscle activity. For example, Grasso et al. [15] examined EMG activity during forward/reversed gait and showed that the first principal component may account for only 50% of the EMG variance and up to 7 principal components had to be used to explain 95% of the inter-trial EMG variance. In addition, PCAs were performed exclusively to extract synergies from unperturbed movements that were executed in a stable environment at a comfortable (quite slow) speed. In this case, EMG signals are time-normalized during PCA or NNMF. This latter procedure renders precise detection of occurrences of motor corrections impossible. Finally, we cannot be sure that linear co-variations extracted from NNMF and PCA are purely representative of motor synergies. For instance, PCA or NNMF performed on EMG signals recorded on both agonist and antagonist muscles during a stretch reflex would extract two synergies: one for the activation of the agonist and the other for the inhibition of the antagonist. Paradoxically, the stretch reflex and the associated combination of agonist and antagonist EMG signals is the clearest evidence and the simplest example of what a single synergy is. Its circuitry is well-known and its temporal organization is stable. By contrast, a method based on the precise detection of the temporal organization between both activation and inhibition would detect strong regularities that would allow classifying this motor sequence as a single synergy.

In more natural conditions, planned movements can be altered at any time if the target location is changed during execution. Given enough time, humans are able to produce fast motor corrections when unexpected events occur during the execution of a movement ([16,17]; see [18] for a review). Motor corrections are usually investigated in the literature by means of a double step pointing experimental paradigm. This framework has indeed been widely employed to understand the numerous processes of feedback control occurring between the eye and the hand during pointing movements [19–21]. To perform such online motor corrections, the CNS uses certain sensory feedback information like the retinal error, which can basically be compared to the efference copy [22–25]. Moreover, such experimental paradigms have also been used to study the temporal delays between the occurrence of a visual perturbation during the initial movement plan and the motor correction. For instance, Paillard [18] established that minimum delays allowing feedback or feedforward control to influence the ongoing movements are classically centered around 120–150 ms when measured on hand kinematics. When measured on EMG signals latencies inferior to 100 ms can be observed both in upper and lower limbs [26].

In this study, our aim was to develop a simple method to determine the precise latencies or delays of each muscle activity in response to a random change in the target location. As muscle synergies would be involved in the following motor corrections, there should exist a temporal link between certain muscle activities, and synergies should be characterized by correlations between the latencies of muscle activities. Consequently, we designed an experiment in which participants were asked to point from an initial sitting position to a target that unexpectedly jumped forward and upward at the same time. The target localization used during the target jump constrained participants to involve their leg, thigh, trunk and arm muscles to perform the task successfully. The investigation of electromyographic activities will thus enable us to determine the temporal aspects of muscular synergies used by the CNS to perform these motor corrections in the whole body.

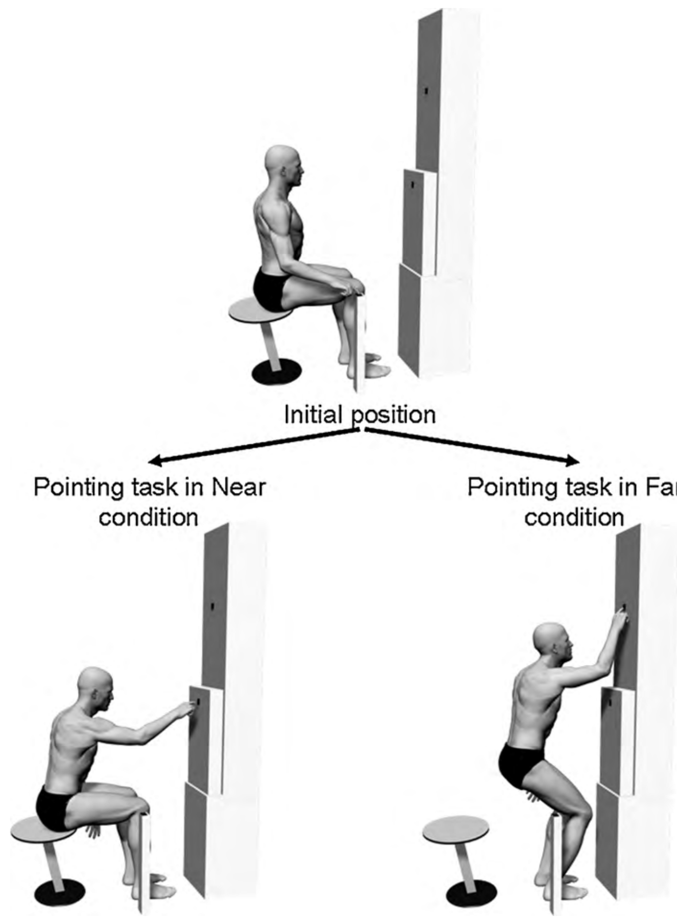

Fig. 1. Experimental pointing task. View from the experimental set-up of the pointing task with the initial position for the three conditions (top) and the final position of the participants when pointing at the near (bottom left) or the far target (bottom right).

2. Materials and methods

2.1. Subjects

Eight right handed participants [all men, 30.5 ± 3 years old, 70 ± 6 kg, 1.76 ± 0.02 m] volunteered for the experiment. None of the participants had a previous history of neuromuscular disease. The entire experiment conformed to the Declaration of Helsinki and informed consent was obtained from all participants according to the guidelines of the University of Burgundy.

2.2. Experimental setup and pointing conditions

Participants were initially seated on a 0.50 m high stool and performed pointing movements with their right index. The starting point, the near and the far targets were represented by small, visual and tactile 10 mm × 10 mm square switches, which could be lit and allowed an accurate detection of time to contact. The starting point was located to the side of the participant's right knee at a 0.50 m distance from the floor, and the near target was located in front of the participant's eyes, in the saggital plane, 0.60 m in front of and 0.50 m higher than the starting point. The far target was located at a total distance of 1.10 m from the starting point, 0.90 m in front of and 0.80 m higher than the starting point. Consequently, the near target could be reached from a seated position whereas the far target necessitated a sit to stand pointing movement (see Fig. 1). Participants were asked to perform their movements as quickly and as accurately as possible when a target was lit, in three experimental conditions. In two normal conditions, either the Near or the Far target (9/21 of all trials for both conditions) was suddenly lit ("go-signal") and remained lit throughout the pointing movement. In the perturbed condition ("Target Jump" condition, 3/21 of all trials), the near target was initially lit and upon hand movement onset, was turned off and the far target was immediately turned