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Electrically-induced muscle fatigue affects feedforward mechanisms of control

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HIGHLIGHTS

- Electromyostimulation impairs movement control.
- Internal representations are not updated following electromyostimulation.
- We question the long-term effects of electromyostimulation on motor control.

ABSTRACT

Objective: To investigate the effects of focal muscle fatigue induced by electromyostimulation (EMS) on Anticipatory Postural Adjustments (APAs) during arm flexions performed at maximal velocity.
Methods: Fifteen healthy subjects performed self-paced arm flexions at maximal velocity before and after the completion of fatiguing electromyostimulation programs involving the medial and anterior deltoids and aiming to degrade movement peak acceleration. APA timing and magnitude were measured using surface electromyography.
Results: Following muscle fatigue, despite a lower mechanical disturbance evidenced by significant decreased peak accelerations (−12%, $p < .001$), APAs remained unchanged as compared to control trials ($p > .11$ for all analyses).
Conclusion: The fatigue signals evoked by externally-generated contractions seem to be gated by the Central Nervous System and result in postural strategy changes which aim to increase the postural safety margin.
Significance: EMS is widely used in rehabilitation and training programs for its neuromuscular function-related benefits. However and from a motor control viewpoint, the present results show that the use of EMS can lead to acute inaccuracies in predictive motor control. We propose that clinicians should investigate the chronic and global effects of EMS on motor control.

1. Introduction

Muscle fatigue is a common sensorimotor state encountered in everyday life. It results in acute motor impairments that are primarily illustrated by a loss of maximal force during voluntary muscle contractions (Gandevia, 2001) and in increased effort to produce a particular force level (Enoka and Stuart, 1992). From a physiological viewpoint, muscle fatigue results in alterations of sarcolemma excitability (Fuglevand et al., 1993) as well as in thermal and metabolic changes (Bigland-Ritchie et al., 1986) that disrupt the functioning of the contractile proteins (Allen et al., 2008). The metabolic changes activate thin sensory fibers, namely group III and IV afferents, which inform the Central Nervous System (CNS) of the current muscular status (Amann, 2011). This fatigue-related information is centrally integrated and inhibits motor brain structures (Taylor et al., 2000), resulting in decreased voluntary activation of the fatigued muscles.

While muscle fatigue is most of the time the consequence of intense and repeated voluntary muscle activations, it can also be externally generated by means of electrically-evoked contractions. Indeed, the use of electromyostimulation (EMS) can generate high

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levels of neuromuscular fatigue. Progressively employed since the 1960s in the field of physical medicine and rehabilitation (see Dolhem, 2008 for an historical review), EMS is now widely used in training programs to improve neuromuscular functions such as maximal strength (Hortobágyi and Maffiuletti, 2011) and endurance (Deley and Babault, 2014). From a global viewpoint, classic EMS programs can lead to loss of Maximal Voluntary Force (MVF) close to 20% (Maffiuletti, 2010). Electrically-evoked contractions, however, result in particular forms of fatigue, as compared to voluntary muscle activations, which depend on the stimulation parameters used (Laufer et al., 2001). For instance, high frequency stimulations have been shown to essentially alter sarcolemma excitability (Badier et al., 1999; Boerio et al., 2005; Zory et al., 2005). In contrast, low frequency stimulations (i.e. stimulations resulting in sub-tetanic contractions) would lead to an important metabolic fatigue (Darques et al., 2003) and to no changes in membrane excitability properties (Badier et al., 1999; Papaiordanidou et al., 2010). At a central level, electrically-evoked contractions have also been shown to significantly impair muscle voluntary activation (Boerio et al., 2005; Papaiordanidou et al., 2010) because of supraspinal rather than spinal alterations (Maffiuletti, 2010; Boerio et al., 2005).

From a motor control view, the effects of a voluntary-induced muscle fatigue have been widely studied and have generally been shown to be compensated by the implementation of adaptive neuromuscular strategies aiming to maintain the initial motor performance during goal-directed movements (Forestier and Nougier, 1998; Côté et al., 2002; Huffenus et al., 2006; Schmid et al., 2006; Missenard et al., 2008). These adaptations have been suggested to arise from the central integration of the group III and IV afferents which would lead to the formulation of fatigue-suited motor strategies (Huffenus et al., 2006). In contrast, when muscle fatigue is electrically-induced, such motor reorganizations do not occur (Huffenus and Forestier, 2006). More precisely, Huffenus and Forestier have shown that the pre-fatigue motion coordination was maintained, reinforcing the activation of impaired muscle without any modification in the initial multi-joint organization. Furthermore, some studies have compared the effects of electrically and voluntarily-induced muscle fatigue on postural control parameters (Paillard et al., 2010a,b; Chaubet et al., 2012). Depending on the nature of the contraction, muscle fatigue of the quadriceps differently affects the postural control (Paillard et al., 2010b). Therefore, it seems that motor control reorganization in the presence of fatigue depends on the way muscle fatigue is elicited, i.e. voluntarily or non-voluntarily.

Rapid arm movements performed in a standing posture require the generation of Anticipatory Postural Adjustments (APAs). These postural strategies are predictive mechanisms of control aiming to counteract in a feedforward fashion the destabilizing effects caused by a voluntary movement (Massion, 1992). Quantitative and temporal features of APAs have been shown to be specific to movement parameters, such as to arm movement direction (Aruin and Latash, 1995), biomechanical (Horak and Nashner, 1986; Aruin, 2006; Li and Aruin, 2007) and temporal constraints (Benvenuti et al., 1997; De Wolf et al., 1998; Slijper et al., 2002), task characteristics (Bonnetblanc et al., 2004) and more interestingly to peak acceleration of the arms (Lee et al., 1987; Bouisset et al., 2000; Mochizuki et al., 2004). This implies that the CNS can predict movement outcome thanks to an internal model of the motor apparatus (Miall and Wolpert, 1996; Desmurget and Grafton, 2000). When efficiently induced, muscle fatigue of a moving limb has been shown to result in significant alterations of the acceleration-generating capacity (Jaric et al., 1997; Corcos et al., 2002; Monjo and Forestier, 2014). During self-paced arm flexions performed at maximal velocity following an isometric fatiguing procedure of the arm flexors, it appears that the CNS is able to accurately predict the mechanical effects of muscle fatigue (Monjo and Forestier, 2014). Indeed, in this study, decreased APAs scaling to the lower postural disturbance were observed during the very first trial post-fatigue, suggesting that forward models incorporate fatigue signals into prediction processes. In the present study, we sought to investigate whether the CNS can accurately predict the mechanical consequences of muscle fatigue when it is externally-induced, i.e. with EMS. For this purpose, participants performed self-generated bilateral arm flexions at maximal velocity before and after fatiguing electrically-evoked contractions aiming to alter the acceleration-generating capacity of the focal muscles. Based on Huffenus and Forestier's results (2006), we hypothesized that externally-generated fatigue signals would result in no APA adaptation.

2. Methods

This study included three different experiments: (1) a main experiment aiming to test our hypotheses and (2) two control experiments investigating the reliability of the main experiment methods.

2.1. Main experiment

2.1.1. Participants

This study included 15 voluntary healthy young men (age: 22.8 ± 0.7 years; height: 1.79 ± 0.02 m; weight: 74.4 ± 2.7 kg) from the physical education department of the Savoie University (UFR-CISM – STAPS). All participants were naive about the tested hypothesis. The study was approved by the local research ethic committee and the subjects' informed consent was obtained in conformity with the declaration of Helsinki (1964) for the experimentations on humans. Prior to the experiments, all the recruited subjects performed a familiarization session during which they experienced electrically-induced contractions (5 min of the EMS program used during the experiments at moderate intensity). It was to ensure that participants were comfortable with evoked-contractions and that they would be able to reach high stimulation intensities.

2.1.2. Experimental procedures and instrumentation

2.1.2.1. Motor task and experimental set up. Participants realized two sets of 6 arm flexions both before and after the EMS procedures described below (Control Block and Fatigue Block) (Fig. 1). During the experimental recordings, participants were asked to stand comfortably on a force platform. The position of their feet was marked to keep an identical stance from one set of trials to another. Subjects had to flex their arms as fast as possible while holding a 0.5 kg metal rod in a self-paced manner within the five seconds following the presentation of an auditory signal. They were instructed to stop their flexion movement at the level of a target placed at eye level. They had to maintain this position until instructed to relax, about 3 s after the completion of the movement.

2.1.2.2. Fatiguing EMS protocol. Electrical stimulations targeted the two primary focal muscles of the arm flexion movement, i.e. the Anterior Deltoid and the Medial Deltoid. During the stimulation protocols, participants seated on a comfortable chair with their hands and forearms attached to the rungs of the chair, the shoulders extended at 30° relative to the trunk (Fig. 2a). This position was selected because it has been shown that muscle fatigue is more efficiently induced when muscle length is longer (Lee et al., 2007).

Electrically-induced contractions were evoked using a conventional electromyostimulator (Theta 500, Compex, France). Two square (5 cm × 5 cm) positive electrodes were bilaterally placed