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Quadriceps mechanomyography reflects muscle fatigue during electrical stimulus-sustained standing in adults with spinal cord injury – a proof of concept

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Abstract: This study investigates whether mechanomyography (MMG) produced from contracting muscles as a measure of their performance could be a proxy of muscle fatigue during a sustained functional electrical stimulation (FES)-supported standing-to-failure task. Bilateral FES-evoked contractions of quadriceps and glutei muscles, of four adults with motor-complete spinal cord injury (SCI), were used to maintain upright stance using two different FES frequencies: high frequency (HF – 35 Hz) and low frequency (LF – 20 Hz). The time at 30° knee angle reduction was taken as the point of critical “fatigue failure”, while the generated MMG characteristics were used to track the pattern of force development during stance. Quadriceps fatigue, which was primarily responsible for the knee buckle, was characterized using MMG-root mean square (RMS) amplitude. A double exponential decay model fitted the MMG fatigue data with good accuracy [$R^2 = 0.85$ – 0.99 ; root mean square error (RMSE) = 2.12 – 8.10] implying changes in the mechanical activity performance of the muscle’s motor units. Although the standing duration was generally longer for the LF strategy (31–246 s), except in one participant, when compared to the HF

strategy, such differences were not significant ($p > 0.05$) but suggested a faster muscle fatigue onset during HF stimulation. As MMG could discriminate between different stimulation frequencies, we speculate that this signal can quantify muscle fatigue characteristics during prolonged FES applications.

Keywords: FES-supported standing; functional electrical stimulation; mechanomyography; muscle fatigue; spinal cord injury.

Introduction

Neuromuscular fatigue is generally defined as an exercise-induced reduction in muscle effort or inability to sustain muscle contractions [1, 2]. During applications of functional electrical stimulation (FES)-evoked muscle activities, such as in the upright stance, the agonist muscles are continuously under electrical stimulation-evoked contractions. This predisposes the stimulated muscles to rapid fatigue, which is the cause of standing failure [3], manifested by a knee buckle.

Traditionally, muscle fatigue during FES-supported standing has been monitored by a change in knee angle [4], and it is this decrease of knee angle that infers a reduction in the muscle’s performance. Moreover, the phenomenon of muscle fatigue has also been investigated by monitoring changes in other characteristics, such as electromechanical indices [5], neurophysiologic and metabolic responses [6]. These have been often measured because a high stimulation intensity and prolonged muscle contractions are characterized by significant alterations in neuromuscular physiology that ultimately leads to reduced performance due to “a reduction in the contractile strength of the muscle fibers and changes in the mechanisms underlying the transmission of muscle action potentials” [2, 7], local muscle oxygenation and metabolite concentrations [8, 9]. However, as “fatiguing contraction” lies within the continuum of effective muscle contractions [10], efforts to improve standing duration warrant the investigation of a possible proxy of muscle fatigue to directly grade muscle performance [11].

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