Medical Engineering and Physics 38 (2016) 767–775

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Torque and mechanomyogram relationships during electrically-evoked isometric quadriceps contractions in persons with spinal cord injury

Morufu Olusola Ibitoye[a,b], Nur Azah Hamzaid[a,*], Nazirah Hasnan[c], Ahmad Khairi Abdul Wahab[a], Md. Anamul Islam[a], Victor S.P. Kean[a], Glen M. Davis[a,d]

[a] Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Biomedical Engineering, Faculty of Engineering and Technology, University of Ilorin, P. M. B. 1515 Ilorin, Nigeria
[c] Department of Rehabilitation Medicine, Faculty of Medicine, University of Malaya, Kuala Lumpur 50603, Malaysia
[d] Clinical Exercise and Rehabilitation Unit, Discipline of Exercise and Sports Sciences, Faculty of Health Sciences, The University of Sydney, Sydney, 2006 NSW, Australia

ARTICLE INFO

Article history:
Received 13 November 2015
Revised 4 May 2016
Accepted 20 May 2016

Keyword:
Mechanomyogram
Spinal cord injury
NMES-evoked muscle contractions
Muscle torque
Motor unit recruitment

ABSTRACT

The interaction between muscle contractions and joint loading produces torques necessary for movements during activities of daily living. However, during neuromuscular electrical stimulation (NMES)-evoked contractions in persons with spinal cord injury (SCI), a simple and reliable proxy of torque at the muscle level has been minimally investigated. Thus, the purpose of this study was to investigate the relationships between muscle mechanomyographic (MMG) characteristics and NMES-evoked isometric quadriceps torques in persons with motor complete SCI. Six SCI participants with lesion levels below C4 [(mean (SD) age, 39.2 (7.9) year; stature, 1.71 (0.05) m; and body mass, 69.3 (12.9) kg)] performed randomly ordered NMES-evoked isometric leg muscle contractions at 30°, 60° and 90° knee flexion angles on an isokinetic dynamometer. MMG signals were detected by an accelerometer-based vibromyographic sensor placed over the belly of rectus femoris muscle. The relationship between MMG root mean square (MMG-RMS) and NMES-evoked torque revealed a very high association ($R^2 = 0.91$ at 30°; $R^2 = 0.98$ at 60°; and $R^2 = 0.97$ at 90° knee angles; $P < 0.001$). MMG peak-to-peak (MMG-PTP) and stimulation intensity were less well related ($R^2 = 0.63$ at 30°; $R^2 = 0.67$ at 60°; and $R^2 = 0.45$ at 90° knee angles), although were still significantly associated ($P \leq 0.006$). Test-retest interclass correlation coefficients (ICC) for the dependent variables ranged from 0.82 to 0.97 for NMES-evoked torque, between 0.65 and 0.79 for MMG-RMS, and from 0.67 to 0.73 for MMG-PTP. Their standard error of measurements (SEM) ranged between 10.1% and 31.6% (of mean values) for torque, MMG-RMS and MMG-PTP. The MMG peak frequency (MMG-PF) of 30 Hz approximated the stimulation frequency, indicating NMES-evoked motor unit firing rate. The results demonstrated knee angle differences in the MMG-RMS versus NMES-isometric torque relationship, but a similar torque related pattern for MMG-PF. These findings suggested that MMG was well associated with torque production, reliably tracking the motor unit recruitment pattern during NMES-evoked muscle contractions. The strong positive relationship between MMG signal and NMES-evoked torque production suggested that the MMG might be deployed as a direct proxy for muscle torque or fatigue measurement during leg exercise and functional movements in the SCI population.

1. Introduction

The study of motor unit (MU) recruitment to evoke force production is of clinical interest, particularly during neuromuscular electrical stimulation (NMES)-evoked contractions of paretic or paralyzed muscles in neurological populations [1]. Incremental MU recruitment during voluntary [2,3] and NMES-evoked contractions [4] has been used to describe muscle force modulation in healthy individuals. However, while NMES-evoked contractions have been utilized for muscle force production in individuals with spinal cord injury (SCI) [5], the mechanical and morphological changes associated with muscle contraction in this population have been poorly documented. To evaluate the effectiveness of NMES interventions, it is important to quantify stimulus-evoked muscle force. In particular, understanding motor recruitment and muscle force characteristics could provide key insights about the contractile properties of the muscle [6] and this has important implications for the use of

* Corresponding author. Tel.: +60 379674487; fax: +60 379674579.
E-mail address: azah.hamzaid@um.edu.my, azah_hamzaid@yahoo.com (N.A. Hamzaid).

http://dx.doi.org/10.1016/j.medengphy.2016.05.012
1350-4533/

NMES in rehabilitation. For example, measuring force or strength changes in persons with SCI can provide evidence of recovery or deterioration of motor output, as well as revealing the efficacy of rehabilitation interventions [7]. Beyond promoting the practical applications of NMES training in maintaining 'muscle health' [8], the ability to quantify an acute increase in muscle force production following NMES exercise [9] could widen the application of this assistive technology in the clinical environment.

Traditionally, isokinetic dynamometers have been used to assess muscle force (via joint torque) in a research setting, and they quantify torque throughout the limb range of motion with acceptable reliability [7]. However, these devices lack portability, and are relatively expensive and cumbersome to deploy for assessments in the clinical or home environment. The estimation of the muscle torque from other muscle characteristics, particularly bio-potentials, becomes an attractive option.

An indirect estimation of torque production has been assessed from electromyography (EMG) [10–12], but sensitivity of the signal to the external electromagnetic interference and skin impedance changes due to perspiration [13] presents significant limitations [14]. Additionally, the reliability of EMG estimation of muscle torque generation during NMES-evoked contraction remains debatable [15], largely due to the size of stimulation artifact current in relation to the EMG signal [10]. Thus, quantification of stimulus-evoked force production by EMG alone during neurostimulation is deficient [16].

A mechanical "counterpart" of the electrical activity of active motor units as measured by EMG (i.e., muscle mechanomyogram; MMG) has been proposed for muscle torque assessments [17,18]. During skeletal muscle contractions, the generated MMG signal is a function of the following mechanisms: "(1) a slow bulk movement of the muscle at the initiation of the contraction, (2) smaller subsequent lateral oscillations occurring at the resonant frequencies of the muscle, and (3) dimensional changes of active muscle fiber" [17]. Therefore, MMG reflects the mechanical activity of physiological phenomena underlying muscle contractions. MMG quantifies neuromuscular performance, and has been used to gain insights into muscle capability during voluntary [17] and stimulated contractions [4]. In healthy humans, Petitjean et al. [4] reported a positive linear relationship between MMG amplitude and MU recruitment (i.e., muscle torque) during incremental NMES-evoked contractions of the first dorsal interosseous muscle (FDI). The authors suggested that the influence of the muscle fiber type may have been responsible for the pattern observed. Consequently, the MMG-torque relationship is both muscle fiber-type composition [19] and structure [20] dependent. In addition, MMG frequency content provides information regarding the firing rates/frequency of the active motor units during voluntary and NMES-evoked contractions [21]. Therefore, simultaneous investigation of the time and frequency contents of MMG signal has been used to interpret motor control strategy that is responsible for muscle force modulation during voluntary [17] and NMES-evoked [14] muscle contractions. Thus, the torque output during NMES-evoked muscle contractions depends on the degree of MU recruitment, their firing rates [4] and the contractile properties of the activated MUs [22]. Nevertheless, clear interpretation of the specific influence of MU recruitment and their firing rates on MMG characteristics during NMES-evoked contractions in individuals with SCI has been minimally investigated.

Thus, the aims of this study were: (1) to quantify the degree of association between MMG signal and isometric torque of the rectus femoris (RF) muscle during incremental NMES-evoked muscle contractions at 30°, 60°, and 90° knee angles; and, (2) to investigate the reliability of MMG signal recorded over RF muscles in persons with SCI. The quadriceps muscle was selected because of its well-established relevance for the study of knee joint torque dynamics [23], could be readily stimulated in paraplegia [24], and could be easily compared with existing data on voluntary contractions [19,25]. RF was selected to represent quadriceps group because it is the major contributor to the NMES-evoked quadriceps muscle torque during knee extension [25,26]. To our knowledge, no previous studies have reported the relationship between MMG parameters and the quadriceps torque production during incremental NMES-evoked isometric contractions in persons with SCI.

We hypothesized that MMG would be a reliable proxy of incremental torque production, since a positive linear relationship has been previously demonstrated in FDI, which is of comparable muscle fiber morphology to the quadriceps [4] with a predominance of type II fibers in this muscle group after SCI [24]. Furthermore, a significant correlation between the MMG signal and muscle torque production would *a priori* support the validity of the signal as a proxy of muscle performance, particularly when a direct measurement of torque might be impractical [15], such as in activities of daily living.

2. Method

2.1. Participants

Nine chronic motor complete (American Spinal Injury Association Impairment Scale A and B) SCI [27] participants with neurological lesions below C4 were recruited at the Department of Rehabilitation Medicine, University of Malaya Medical Centre, Kuala Lumpur, Malaysia. Their written informed consent was obtained after a full disclosure of the rational and procedures of the experiment in compliance with the declaration of Helsinki. They were duly informed about the possible sources and discomforts of the dynamometer assessment and electrical stimulation, and were advised of their rights of withdrawal from the study at any time. Individuals with severe spasticity, joint contracture or lower motor neuron lesion that might adversely affect the production of modest quadriceps torque were excluded from participation. Also excluded were any participants who, as a result of incremental NMES current amplitude, produced no relative increase in their stimulus-evoked torque values. Of the nine participants recruited at the outset, only seven successfully completed the full test battery. However, a further participant was excluded due to lack of increase in relative torque in response to increasing NMES current intensity. Therefore, the data of the remaining six participants (Table 1) has been included for analysis. All participants retained quadriceps spinal reflexes, and they could sit up on a dynamometer's chair with backrest. As part of clinical conditioning exercises [28], at the time of the investigation, participants were already involved in NMES cycle training (2 to 3 times per week for at least 7 weeks), but were asked to refrain from the training for at least 48 hours before testing.

2.2. Experimental protocol

Participants were secured to a calibrated isokinetic dynamometer (System 4; Biodex Medical Systems, Shirley, NY, USA) by an inextensible restraining straps over the thigh, pelvis and the trunk to minimize extraneous movements [29] and to ensure only isometric contractions of the quadriceps could be performed (Fig. 1) [28]. Based on safety considerations of not putting bone health at risk [30], and to analyze the muscle torque in a range that will mimic functionally relevant mode such as in standing up, we utilized maximal torque calculations based on the empirical data of Kagaya and colleagues [31]. Those investigators suggested that the knee extensor's moment should not exceed that required for NMES standing in persons with SCI. Thus, careful attempts were made to keep the NMES-evoked muscle torque production within