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Research Report

Force frequency structure below 1 Hz in chronic stroke: Paretic arm control

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ABSTRACT

This study investigated force variability and frequency structure below 1 Hz to determine whether coupled bilateral training and neuromuscular stimulation facilitated force control in paretic arms. Fifteen chronic stroke participants received 9 h of coupled bilateral movement training. Unilateral and bilateral force control tasks were administered before and after rehabilitation. Repeated measures ANOVAs were performed on the: (a) coefficient of variation and (b) absolute and relative power below 1 Hz in the paretic hand. Further, a multiple linear regression analysis determined the relationship between the coefficient of variation and frequency power. Three significant rehabilitation findings indicated: (a) reduced force variability across unilateral and bilateral force control conditions, (b) decreased absolute power in 0.09–0.41 Hz and 0.59–1.08 Hz whereas increased relative power in 0.59–1.08 Hz during unilateral force control, and (c) reduced absolute and relative power in 0.09–0.41 Hz that were associated with decreased variability during both unilateral and bilateral force control. Improved force variability in controlling unilateral paretic arms after training was attributed to less power below 0.41 Hz. Reorganization of the force frequency structure appears as a prominent component in force control improvements in paretic arms.

1. Introduction

Upper extremity motor impairments post stroke severely limit movement capabilities. Indeed, unilateral paresis caused by a stroke interferes with motor actions required in many daily activities including force control (Kamper and Rymer, 2001; Lodha et al., 2010; Nowak, 2008). Thus, improving force control capabilities post stroke has become a primary rehabilitation goal.

Previous force control studies reported impairments in stroke survivors at submaximal target force level (e.g., 5–50% of maximum voluntary contraction) (Lodha et al., 2010, 2012b). These findings include an exaggerated force variability (i.e., coefficient of variation: CV) by a stroke group in comparison to an age-matched control group. Explanations of the variation in force output focused on the discharge rates and synchronization of motor units, impaired cortical activation, and weaker muscle strength (Lodha et al., 2010; Moritz et al., 2005; Sosnoff et al., 2006; Taylor et al., 2003). Moreover, Lodha et al. (2010) found reduced force control variability in the upper extremities as the severity of motor impairments decreased.

Abbreviations: SD, standard deviation; CV, coefficient of variation; EMG, electromyography; MVC, maximum voluntary contraction; SLS, significant level to stay

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The frequency structure of force outputs indicates distribution of absolute (N^2) and relative power (%) within specific frequency ranges. Exploring the frequency structure of forces holds promise in advancing our understanding force control. Low frequency oscillations (0–4 Hz), readily decrease task variability during submaximal force contractions (Keogh et al., 2006; Tracy et al., 2007; Vaillancourt and Newell, 2003). Moreover, recent force control studies demonstrated that the frequency patterns below 1 Hz were strongly associated with force variability (Baweja et al., 2010; Fox et al., 2013). When elderly participants displayed increased force variability, relative power in 0–0.41 Hz increased whereas relative power in 0.59–1.08 Hz decreased. In contrast, younger adults revealed less relative power in 0–0.41 Hz and greater in 0.59–1.08 Hz than an elderly group. Consequently, less relative power in 0–0.41 Hz and greater relative power in 0.59–1.08 Hz were associated with decreased force variability (Fox et al., 2013).

The relationship between frequency structure below 1 Hz and force variability may be associated with synaptic noise, motor unit discharge rates, and sensorimotor processing (Dideriksen et al., 2012; Fox et al., 2013). Elderly adults typically show greater synaptic noise that contributed to increased discharge rate variability in the motor units (Christou et al., 2007; Dideriksen et al., 2012; Fox et al., 2013; Tracy et al., 2005). Further, Dideriksen et al. (2012) reported that the effect of synaptic noise on discharge rate variability increased when frequency oscillations below 1 Hz in the motor neuron pool were activated. Thus, greater relative power in 0 – 0.41 Hz in the elderly adults may contribute to increased synaptic noise causing greater variability in force. Indeed, Keogh et al. (2006) reported that greater power in 0 – 1.5 Hz in the elderly adults was associated with deficits in ability to process and integrate sensorimotor information rather than impaired sensory functions. This evidence suggests that modulation of frequency patterns below 1 Hz may be crucial to minimizing force variability.

The relationship between force frequency patterns below 1 Hz and variability serves as a compelling reason to investigate the structure of force frequency in stroke survivors. Lodha et al. (2013) demonstrated that force variability in a stroke group was significantly greater than an age-matched control group, and the increased variability was associated with the force frequency structure below 1 Hz. Moreover, the stroke group displayed greater relative power in 0 – 0.3 Hz and less relative power in 0.6 – 1.0 Hz than the age-matched group. Indeed, a similar force frequency structure below 1 Hz was found between the more impaired and less impaired hands. The more impaired hand displayed greater relative power in 0 – 0.3 Hz in comparison to the less impaired hand whereas less relative power in 0.6 – 1.0 Hz was found in the more impaired hand. Increased relative power below 0.3 Hz in the stroke group may be attributed to greater synaptic inputs, after-hyperpolarization potential post stroke, or impaired sensorimotor processing (Dideriksen et al., 2012; Fox et al., 2013; Liang et al., 2010; Lodha et al., 2013). Moreover, previous studies reported that the excessive force variability in the paretic hand post stroke decreased after rehabilitation training (Cauraugh et al., 2009, 2011; Massie et al., 2013). Thus, these findings lead to the question: Is reduced force variability after training associated with a reorganized frequency structure below 1 Hz (e.g., less power below 0.41 Hz and greater power above 0.59 Hz)?

The purpose of this study was to investigate force variability and frequency structure below 1 Hz to determine whether coupled bilateral movement training facilitates force control in paretic arms. For frequency analysis of force production, power spectrum analyses were calculated with seven frequency bands (e.g., resolution of each frequency band = 0.166 Hz) below 1 Hz (Fox et al., 2013). Coupled bilateral movement training and active neuromuscular stimulation on the muscles of the paretic arms were selected as the rehabilitation protocol because of evidence supporting motor improvements in the paretic arms (Cauraugh et al., 2009, 2010; Kimberley et al., 2004). Previous studies reported improved motor capabilities as seen in a higher number of blocks moved and faster motor reaction times post rehabilitation (Cauraugh et al., 2010; Hara, 2008; Smith and Staines, 2006). Moreover, chronic stroke patients who received coupled bilateral movement training revealed a reduction in force variability produced by the paretic arms during a sustained force production task in comparison to the control group (e.g., no neuromuscular stimulation intervention) (Cauraugh and Kim, 2003, 2009). Thus, the coupled bilateral movement protocol was expected to decrease force variability and change low force oscillations in paretic arms.

For the submaximal force control task administered before and after the training, participants executed unilateral and bilateral wrist and fingers extension movements. Given that stroke survivors typically have difficulty activating extensor muscles while displaying a restricted range of motion, a wrist and fingers extension task that involved isometric force control served as a valid measure in assessing progress toward recovery (Lang et al., 2009; Lodha et al., 2010, 2012a). Moreover, paretic hand function was measured during unilateral as well as bilateral movements because the role of paretic hand for force control varied with the movement condition (DeJong and Lang, 2012).

Consistent with Kelso's definition (Kelso, 1984), bilateral coordination occurs when two arms work together and are coordinated as a unit (e.g., two coupling patterns: in-phase coordination and anti-phase coordination). An underlying mechanism for bilateral coordination involves inter-hemispheric crosstalk. During bilateral movements, excitatory or inhibitory activities from two hemispheres interact via callosal connections. Coupling patterns occur when inter-hemispheric excitation or inhibition balanced between hemispheres (Cardoso de Oliveira, 2002). Thus, successful coordination patterns improve bilateral performance (e.g., force variability) whereas dysfunctions in the callosal connections (e.g., callosotomy patients) and unbalanced excitatory or inhibitory activities between hemispheres compromise coordination patterns between hands (Cauraugh and Summers, 2005; Houweling et al., 2010).

For stroke survivors, bilateral force control deficits (e.g., impaired coordination and greater force variability) are associated with unbalanced inter-hemispheric inhibitions between hemispheres (e.g., greater inter-hemispheric inhibition from the contralesional hemisphere than the ipsilesional hemisphere) (Cauraugh and Summers, 2005; Kilbreath et al., 2006; Stinear and Byblow, 2004). Further, previous bilateral