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EVIDENCE FOR BETA CORTICOMUSCULAR COHERENCE DURING HUMAN STANDING BALANCE: EFFECTS OF STANCE WIDTH, VISION, AND SUPPORT SURFACE

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Abstract—The role of the cerebral cortex in maintaining human standing balance remains unclear. Beta corticomuscular coherence (CMC) provides a measure of communication between the sensory-motor cortex and muscle, but past literature has not demonstrated significant beta CMC during human stance. This study evaluated the effects of stance width, vision, and surface compliance on beta CMC during human stance using methods to enhance sensitivity to CMC. Ten healthy, young adults stood for three 60-s trials in each of a wide or narrow stance width while on a firm surface and in narrow stance on a foam surface, each with eyes open or closed. Beta CMC was calculated between contralateral electroencephalographic and electromyographic recordings. Electromyography was recorded from bilateral tibialis anterior and gastrocnemius lateralis muscles. CMC magnitude was defined as the average integrated area of coherence spectrum above a significance threshold. Measures of center-of-pressure (COP) sway were derived from force plates under the subjects' feet. Results of CMC from four muscles across six stance conditions (a total of 24 combinations) demonstrated significant average CMC magnitude from every subject in 20 combinations and significant average CMC magnitude in nine of 10 subjects in the remaining four combinations. The CMC magnitude was significantly larger in the wide-stance condition than in the narrow-stance condition with eyes open. No significant differences were detected when comparing eyes-open to eyes-closed conditions or when comparing firm- to foam-surface conditions. Correlations between CMC magnitude and COP sway elicited some significant relationships, but there was no consistent direction or pattern of correlation based on muscle or stance condition. Results demonstrate that significant beta CMC is evident during human standing balance, and that beta CMC is responsive to changes in mechanical, but not visual or surface, conditions.

Key words: corticomuscular coherence, standing balance, posture, cortex, EEG, EMG.

INTRODUCTION

It is essential to understand the neural mechanisms of human standing balance in order to adequately interpret and treat balance disorders and to enable more accurate programing of bipedal robotics or neuroprosthetics. The role of the cerebral cortex in human standing balance remains unclear. Although decerebrate preparations of quadruped animals demonstrate a strong capacity to maintain standing balance without cortical resources (Mori, 1987; Musienko et al., 2008; Honeycutt et al., 2009), that capacity does not necessarily determine lack of cortical utilization in intact preparations, and such control may not generalize to the biomechanically more challenging condition of human bipedal stance (Skoyles, 2006).

Indeed, multiple human-subject studies suggest a potential role for the cerebral cortex in the control of human standing balance. Specifically, standing balance is impaired by stroke to the cerebral cortex, particularly with regard to the integration of sensory input for the control of postural sway (Pérennou et al., 2000; Bonan et al., 2004). With regard to healthy subjects, studies of transcranial magnetic stimulation and neuroimaging demonstrate that standing balance associates with enhanced cortico-cortical and cortico-spinal excitability or with enhanced cerebral blood flow compared to non-standing or supported conditions (Obata et al., 2009; Ouchi et al., 1999; Tokuno et al., 2009). Changes in corticospinal excitability, however, are not consistently identified (Daikuya et al., 2003). Studies of electroencephalography (EEG) have identified changes in EEG oscillation frequencies across many functional bands during quiet stance (Thibault et al., 2014), suggesting altered synchronized communication of cortical circuitry, and some studies have demonstrated changes in EEG rhythms in different visual conditions (Del Percio et al., 2007) or when

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Abbreviations: AP, anterior–posterior; CMC, corticomuscular coherence; COP, center of pressure; EEG, electromyography; EMG, electroencephalography; FEC, test condition of standing in narrow stance width on a foam surface with eyes closed; FEO, test condition of standing in narrow stance width on a foam surface with eyes open; GL, gastrocnemius lateralis; ML, medial–lateral; NEC, test condition of standing in narrow stance width on a firm surface with eyes closed; NEO, test condition of standing in narrow stance width on a firm surface with eyes open; TA, tibialis anterior; WEC, test condition of standing in wide stance width on a firm surface with eyes closed; WEO, test condition of standing in wide stance width on a firm surface with eyes open.

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spontaneously transitioning from stable to unstable stance (Slobounov et al., 2009; Varghese et al., 2015). Thus, the cerebral cortex appears involved in human standing balance at least for the purpose of monitoring postural status and perhaps also in its subsequent control. Changes in cortical excitability, hemodynamic response, or EEG oscillations, however, do not necessarily signify direct control by the cerebral cortex on standing balance.

In an effort to establish a direct functional connection between muscle and the cerebral cortex during human standing balance, some studies have examined corticomuscular coherence (CMC) (Masakado et al., 2008; Vecchio et al., 2008; Murnaghan et al., 2014). CMC is a measure whereby time-varying spectral power from signals of cortical and muscle function is correlated. CMC of the beta frequency band (roughly 13–30 Hz) is most studied, often during tasks of tonic, low-to-moderate levels of contraction, and found to represent both afferent and efferent coupling between sensory-motor regions of cerebral cortex and muscle (Mima and Hallett, 1999a,b, Mima et al., 2000; Witham et al., 2011; Campfens et al., 2013). Studies of CMC during human standing balance, however, did not demonstrate the existence of significant beta CMC (Masakado et al., 2008; Murnaghan et al., 2014), although one has identified the existence of alpha (8–12 Hz) CMC, which varied between groups of differing athletic training and visual conditions (Vecchio et al., 2008). In contrast to beta CMC, the alpha CMC is less specific to functions of the sensory-motor cortex and relates to perceptual processing over association cortex.

Lack of significant beta CMC during stance may relate to either the methods of collection and processing or to the limited contexts of evaluated standing tasks. In specific, the studies that focused on evaluating beta CMC (Masakado et al., 2008; Murnaghan et al., 2014) (a) analyzed EEG data only over the vertex electrode and/or at one electrode just rostral to the vertex, (b) examined stance of unknown width or one-legged stance, (c) examined stance with a backboard support that either constrained sway or moved with the individual affixed to it, (d) evaluated only ankle plantarflexors, and (e) did not necessarily utilize processing techniques that enhance CMC (Mima and Hallett, 1999b). Because beta CMC is known to be strongly dependent on the individual, the task and type of muscle contraction elicited, the chosen muscle, as well as the location of EEG electrodes, more comprehensive study designs are needed in order to adequately assess beta CMC during human stance (Ushiyama et al., 2010, 2011, 2012; Gwin and Ferris, 2012; Campfens et al., 2013).

Therefore, the objectives of this study were to (1) identify the existence of beta CMC during human standing balance through methods that enhance sensitivity and (2) identify the functional relevance of beta CMC to human standing balance through variations in sensory and biomechanical constraints. We sought to enhance sensitivity of identifying beta CMC by (a) conforming to suggested methods of processing (Mima and Hallett, 1999b), (b) evaluating both ankle plantar- and dorsi-flexor muscles, (c) accounting for inter-individual variability by evaluating each individual's electrode of maximal CMC across a broader set of electrodes overlying the sensory-motor cortex, (d) evaluating the integrated area of the CMC spectrum over a statistical threshold rather than peak CMC amplitudes, and (e) accounting for previously untested standing task conditions by varying stance width, vision, and surface compliance. We sought to identify the functional relevance of beta CMC to human standing balance by demonstrating its modulation to altered balance constraints between conditions of stance width, vision, and surface compliance, as well as through exploratory correlations with center-of-pressure (COP) measures of sway. We hypothesized that corticomuscular coupling does exist and that it is functionally relevant to standing balance. We, therefore, predicted non-zero CMC magnitude above the significance threshold across balance conditions as well as significant effects of stance conditions on beta CMC and significant correlations between beta CMC magnitudes and COP sway. Understanding the mechanisms by which the sensorimotor cortex communicates with muscle through beta CMC during human standing balance could offer important insight into causes of impaired balance with disease or injury and potentially provide a biomarker for such impairment or for improvement with clinical interventions.

EXPERIMENTAL PROCEDURES

Subjects

Ten healthy young subjects (five males, five females; mean (range) age = 23 (20–29) year, height = 170 (152–183) cm, weight = 69 (48–88) kg; nine right leg dominant) provided written informed consent to participate in the protocol, which was approved by the local institutional review board. Subjects were recruited via postings on internet forums and community bulletin boards. Subjects were included based on a self-report if they were non-smokers with no known history of neurological, musculoskeletal or psychiatric disorders, no cancer or cancer treatment, and were not taking any centrally active medications.

Protocol

Subjects were first prepared for testing. Following shaving and cleaning with a conductive gel to obtain impedances below 10 kΩ, bipolar surface electromyography (EMG) electrodes (1-cm silver/silver-chloride disk electrodes with fixed 2-cm inter-electrode distance; Myotronics, Kent, WA, USA) were applied according to the SENIAM guidelines (http://www.seniam.org/) along the length of the contracted muscle bellies of the left and right tibialis anterior (TA) and gastrocnemius lateralis (GL). These muscles were chosen for the study because (1) these muscles provide complimentary plantarflexor and dorsiflexor activation for modulating multidirectional postural sway, (2) each muscle is known to generate CMC during other tasks, and (3) these distal muscles do not require filtering against cardiac artifact. Specifically, the GL was chosen for recording because it