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Research report

Muscle synergies involved in shifts of the center of pressure while standing on a narrow support

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Abstract

We investigated multi-muscle synergies during preparation to push a load forward and their changes with different support conditions. We hypothesized that the subjects show unchanged mode structure and would be able to form multi-mode COP stabilizing synergies while standing on an unstable board. Eight healthy subjects participated in the study. Standing subjects performed load-pushing tasks under two conditions, "normal support" and "ML narrow support". Electromyographic (EMG) signals of 12 postural muscles were recorded and analyzed. The participants also performed standard tasks associated with releasing a load. These trials were used to identify muscle groupings (M-modes) associated with shifts of the center of pressure (COP) and relations between small changes in the M-modes and COP shifts in different support conditions. The subjects showed unchanged mode structure across different support conditions. The framework of the uncontrolled manifold hypothesis was used to partition the EMG variance across load-pushing trials into two components that kept constant and changed the COP coordinates in the anterior–posterior (AP) direction. This analysis has allowed us associate changes in the contribution of muscles with COP shifts under different support conditions. Different time profiles of the synergies were observed related to the COP shifts across conditions. This outcome supports a view that indices of multi-muscle (multi-M-mode) synergies can show anticipatory changes in preparation for a predictable perturbation.

Keywords: Posture; Synergy; Standing; Electromyogram; Principal component analysis; Uncontrolled manifold; Narrow support; Human

1. Introduction

Upright human posture is inherently unstable due to the difficulty in maintaining the high center of gravity (two-third of the body mass is located at or above 54–58% of the body height from the ground [28]) on the relatively small base of support provided by the feet. Voluntary movements such as forward body sway and interactions with external objects challenge the whole-body's equilibrium and threaten vertical postural balance. Obviously, when voluntary movements are made while standing, the center of pressure (COP, the point of application of the resultant force acting on the body from the supporting surface) cannot be shifted beyond the available dimensions of the support area [6,11,20]. In particular, when standing on boards with a decreased dimension of the support area in the medio-lateral (ML) direction ("unstable board"), the activity of postural muscles has to be adjusted to constrain COP shifts and maintain the whole-body balance.

Since the classical works by Hughlings [12], researchers have agreed that muscles are not controlled independently by the brain but are organized in groups manipulated by a smaller number of variables as compared to the number of muscles. Bernstein [8] used the notion of synergies as the means of solving the problem of motor redundancy, i.e. of decreasing the number of variables the controller needs to manipulate. Recently, an uncontrolled manifold (UCM) approach [18,22] has been developed to analyze multi-muscle synergies based on changes in the muscle activation patterns (electromyographic signals, EMGs) [15,16,25]. This approach assumes that the central nervous system (CNS) co-varies the involvement of muscle groups across trials to stabilize a desired COP shift. According to the UCM approach, the controller acts in a state space of orthogonal elemental variables and selects in that space a sub-space (a manifold, UCM) corresponding to a value of a performance vari-

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able that needs to be stabilized. Then, it arranges co-variation among the elemental variables such that their variance has relatively little effect on the selected performance variable, i.e. it is mostly confined to the UCM. In studies of EMG patterns in postural tasks, elemental variables have been associated with muscle groups within which muscle activation levels scaled in parallel (muscle modes, M-modes [16,25]), while performance variables were associated with COP coordinates. Those studies confirmed the existence of multi-mode synergies stabilizing time shifts of the COP across a variety of postural tasks [26].

When subjects stand in challenging conditions, for example on a board with a decreased support area ("unstable board"), they show significant changes in the control of vertical posture. In particular, standing in such conditions is associated with larger postural sway [17,20] and smaller anticipatory postural adjustments (APAs) [5,21]. Within the general scheme of synergies originally introduced by Gelfand and Tsetlin [9], elemental variables are themselves synergies at a different level of analysis. Synergies are based on co-variation of elemental variables that are assumed to be relatively stable associated with motor actions that the synergies stabilize. Previous studies have shown changes in the index of multi-M-mode synergies during the execution of such tasks as making a step and voluntary sway [25–27]. These studies assumed that no changes in the composition of M-modes happened during the execution of such tasks. This assumption has been indirectly corroborated by the observations of similar M-modes in several studies using variations of postural tasks [16,25–27]. When standing in challenging conditions, muscle synergies can be expected to require stabilizing COP displacements. Therefore, we hypothesized that the subjects would show unchanged mode structure and would be able to form multi-mode COP stabilizing synergies while standing on an unstable board with a decreased dimension of the support area in the medio-lateral direction.

2. Methods

2.1. Subjects

Eight healthy subjects, six males and two females, mean mass 65.2 kg (±12.5 S.D.), mean height 171.9 cm (±10.9 S.D.) and mean age 28.5 years (±6.6 S.D.), without any known neurological or motor disorder, participated in the experiment. All subjects were right-handed according to their hand usage during eating and writing. All of them were right foot dominant. The tests used to determine the dominant foot included kicking a ball, stepping up on a stair, and leading off in the long jump. The subjects gave written informed consent according to the procedure approved by the Office for Regulatory Compliance of the Pennsylvania State University.

2.2. Apparatus

A force platform (AMTI, OR-6, Watertown, MA, USA) was used to record the moment around the medial-lateral axis (M_y), the vertical component of the reaction force (F_z), and the shear force (F_x) in the anterior–posterior (AP) direction. The subjects stood barefoot on the force platform or on a specially constructed wooden board (the "unstable board") with the same horizontal dimensions as the force plate. The board (Fig. 1) was fitted with a narrow beam on the undersurface (3.3 cm wide, 5.0 cm high). This board was placed over the force platform such that its narrow dimension was in the medio-lateral direction. The dimensions of the supporting beam making contact with the force platform were within the dimensions of the platform.

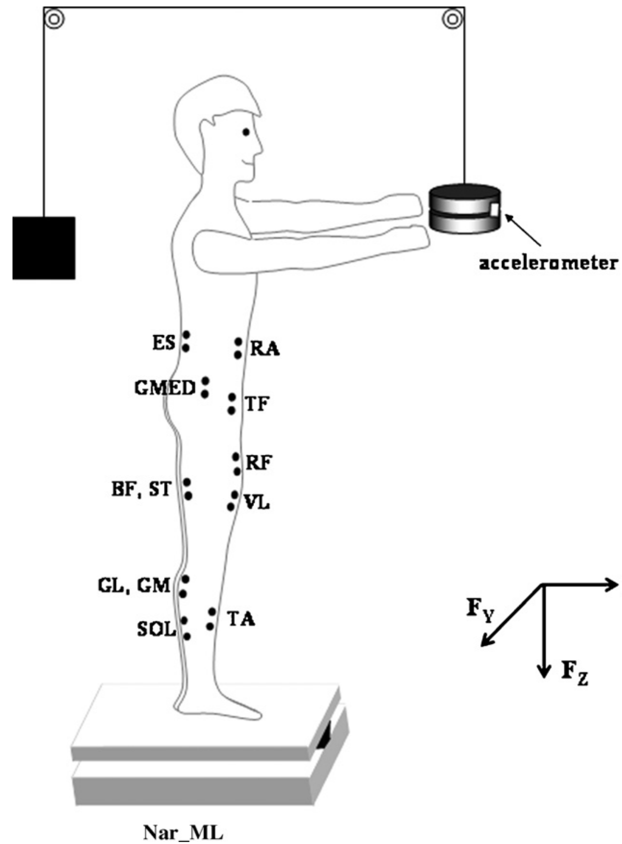

Fig. 1. The experimental setup. The subjects stood barefoot on the force platform or on a specially constructed wooden board (the "unstable board") with the same horizontal dimensions as the force plate. The board was fitted with a narrow beam on the undersurface. This board was placed over the force platform such that its narrow dimension was in the medio-lateral direction. The subject was instructed to lean forward and push the load suspended in front of the body with both hands of the extended arms. Location of some of the EMG electrodes is also shown (GL, lateral head of gastrocnemius; GM, medial head of gastrocnemius; SOL, soleus, ST, semi-tendinosus; BF, biceps femoris; GMED, gluteus medius; ES, erector spinae; TA, tibialis anterior; VL, vastus lateralis; RF, rectus femoris; TF, tensor fasciae latae; RA, rectus abdominis).

Disposable self-adhesive electrodes (3 M) were used to record the surface EMG of the following postural muscles from the right side of the body: lateral head of gastrocnemius (GL), medial head of gastrocnemius (GM), soleus (SOL), semi-tendinosus (ST), biceps femoris (BF), gluteus medius (GMED), erector spinae (ES), tibialis anterior (TA), vastus lateralis (VL), rectus femoris (RF), tensor fasciae latae (TF), and rectus abdominis (RA). The electrodes were placed on the muscle bellies, with their centers 3 cm apart. In addition, a reference electrode was attached to the proximal end of the shank. The EMG signals were amplified by means of differential amplifiers (3000×). The data were digitized at the sampling frequency of 1000 Hz with a 12-bit resolution. A Gateway 450 MHz PC with customized software based on the LabView-5 package (National Instruments, Austin, TX, USA) was used to control the experiment and collect the data.

In some conditions the subjects held a light-weight handle in front of their body by pressing on its sides with both hands. The handle was connected to a load via a pulley system such that the load created a force acting upwards. A uni-directional accelerometer (Sensotec, Columbus, OH, USA) was taped on the load and used for trial alignment (see later). The axis of sensitivity of the accelerometer was directed along the motion of the load.

2.3. Procedures

Four types of tasks were used. Two tasks were associated with anticipatory postural adjustments preceding a quick load release (LR) action; they involved