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The influence of locomotor rehabilitation on module quality and post-stroke hemiparetic walking performance

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ABSTRACT

Recent studies have suggested the biomechanical subtasks of walking can be produced by a reduced set of co-excited muscles or modules. Individuals post-stroke often exhibit poor inter-muscular coordination characterized by poor timing and merging of modules that are normally independent in healthy individuals. However, whether locomotor therapy can influence module composition and timing and whether these improvements lead to improved walking performance is unclear. The goal of this study was to examine the influence of a locomotor rehabilitation therapy on module composition and timing and post-stroke hemiparetic walking performance.

Twenty-seven post-stroke hemiparetic subjects participated in a 12-week locomotor intervention incorporating treadmill training with body weight support and manual trainers accompanied by training overground walking. Electromyography (EMG), kinematic and ground reaction force data were collected from subjects both pre- and post-therapy and from 19 age-matched healthy controls walking on an instrumented treadmill at their self-selected speed. Non-negative matrix factorization was used to identify the module composition and timing from the EMG data. Module timing and composition, and various measures of walking performance were compared pre- and post-therapy.

In subjects with four modules pre- and post-therapy, locomotor training resulted in improved timing of the ankle plantarflexor module and a more extended paretic leg angle that allowed the subjects to walk faster and with more symmetrical propulsion. In addition, subjects with three modules pre-therapy increased their number of modules and improved walking performance post-therapy. Thus, locomotor training has the potential to influence module composition and timing, which can lead to improvements walking performance.

1. Introduction

Stroke is the leading cause of long-term disability in the United States [1]. Although the manifestations of disability post-stroke vary, several features of hemiparetic gait are common, including diminished speed, increased duration of stance on the non-paretic limb, increased duration of double support and asymmetric joint kinematics and kinetics [2,3]. Because improved walking ability is central to rehabilitation of stroke patients [4], assessments are needed to evaluate walking performance throughout the rehabilitation process. Previous assessments have compared self-selected walking speed [5], propulsive and braking impulses [6], paretic leg propulsion [6], step length asymmetry [7,8] and pre-swing leg angle [9]. Since gait impairments are the result of deficient neuromuscular control, we have recently focused on quantifying the neuromuscular control deficits exhibited by individuals post-stroke. In healthy adults and persons post-stroke, we have shown that the biomechanical subtasks of walking (e.g., body support, forward propulsion, leg swing and mediolateral balance control) are produced by co-activated muscles or modules [10,11]. In healthy adults these modules are activated independently. In contrast, individuals post-stroke exhibit poor inter-muscular coordination characterized by co-activation (timing overlap) of modules that are independent in healthy individuals [12]. Given that modules control the biomechanical subtasks of movement, this finding suggests the biomechanical subtasks of

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walking are interfering with one another. Greater interference between subtasks is expected to lead to poorer walking performance while less interference is expected to lead to better walking performance. Indeed, we found a higher number of modules post-stroke was positively associated with better performance in various clinical and biomechanical assessments of walking, including walking speed, ability to change walking speed (increase from preferred to fast), dynamic gait index, step length symmetry and propulsion symmetry [12,13]. Thus, improvements in modular organization during rehabilitation may lead to a more normal gait pattern and improved walking performance.

In healthy adults, analyses of the modular organization have revealed that well-coordinated walking can be produced by exciting 4 co-activation modules: module 1 (hip and knee extensors) in early stance, module 2 (ankle plantarflexors) in late stance, module 3 (tibialis anterior and rectus femoris) during swing, and module 4 (hamstrings) in late swing and early stance, with each module providing essential biomechanical functions [11]. Persons with post-stroke hemiparesis typically have fewer modules that are less organized than in healthy individuals [12]. Even in those individuals who have four modules post-stroke, the modules differ in composition (i.e., the relative weighting of each muscle in each module) and timing (i.e., the activation of those modules over the gait cycle) from those of healthy individuals, which likely adversely affects their walking ability. Although we have shown that independent activation of modules is important, it is also necessary to ensure that the quality of modules is appropriate with regard to timing and composition. Indeed, individuals post-stroke who have an appropriate number of modules often exhibit walking deficits relative to healthy individuals [12]. Therefore, improvement of the composition and timing of their modular organization such that it better matches the organization of healthy subjects could significantly improve locomotor performance.

However, whether locomotor therapy can improve module composition and timing and if these improvements lead to better walking performance is unclear [e.g., 14]. Therefore, the goal of this study was to examine the influence of a locomotor rehabilitation therapy on module composition and timing and walking performance in post-stroke hemiparetic subjects. Specifically, we assessed whether those subjects with four modules pre-therapy improved their post-therapy module composition and timing and walking performance. In addition, we compared module composition and timing post-therapy in all subjects with four modules post-therapy, grouped by pre-therapy number of independent modules, to determine whether the number of modules an individual had pre-therapy influences their post-therapy modular organization and biomechanical measures of gait performance. Specific measures of gait performance included self-selected walking speed, paretic step length asymmetry, paretic pre-swing leg angle and propulsion asymmetry.

2. Methods

2.1. Participants

Study participants were a subset from a larger study on the effects of locomotor training post-stroke [15]. Twenty-seven post-stroke hemiparetic subjects participated in a 12-week, 36 session locomotor training program that included stepping on a treadmill with body weight support and manual assistance [15]. The inclusion criteria were: stroke within 6 months to 5 years; hemiparesis secondary to a single unilateral stroke (Fugl–Meyer LE score < 34); no significant lower extremity joint pain, range of motion limitations, or major sensory deficits; able to walk independently with an assistive device over ten meters on a level surface; able to walk on a daily basis in the home; no severe perceptual or cognitive deficits; no significant lower limb contractures; and no significant cardiovascular impairments contraindicative to walking. Data from a single walking session were acquired from 19 aged-matched healthy subjects. All subjects provided informed consent to an institutionally approved protocol.

2.2. Experimental set-up and procedure

Subjects performed 30-s walking trials on a split-belt instrumented treadmill (Techmachine, Andrézieux Boutheon, France) at their self-selected speed both pre- and post-therapy. Practice trials were performed to ensure subjects were comfortable with the experimental setup. Subjects walked approximately 10-s prior to each data collection to ensure they had reached a steady-state walking pattern. Reflective kinematic markers were placed on the limbs and torso using a modified Helen Hayes marker set. Marker locations were recorded in three dimensions at 100 Hz using a twelve-camera motion capture system (Vicon Motion Systems). A 16-channel EMG system (Konigsburg Instruments, Pasadena, CA) was used to record EMG data at 2000 Hz bilaterally from the tibialis anterior (TA), soleus (SO), medial gastrocnemius (MG), vastus medialis (VM), rectus femoris (RF), medial hamstrings (MH), lateral hamstrings (LH), and gluteus medius (GM). Bilateral 3D ground reaction forces (GRFs) were recorded at 2000 Hz.

2.3. Data analysis

Kinematic and kinetic data were processed using Visual3D (C-Motion, Inc., Germantown, MD). Kinematic and GRF data were low-pass filtered using a fourth order Butterworth filter with cutoff frequencies of 6 Hz and 20 Hz, respectively. EMG was high pass filtered with a cutoff frequency of 40 Hz, de-meaned, low pass filtered with a cutoff frequency of 10 Hz using a 4th order Butterworth filter and normalized to its peak values. Gait cycle time was determined from the GRF data. All data were time normalized to 100% of the gait cycle.

Biomechanical and EMG measures were analyzed using Matlab (The Mathworks, Natick, MA). Pre-swing leg angle was computed as the maximum angle between a line from the pelvis center-of-mass to the foot center-of-mass and vertical (positive when foot is posterior to the pelvis) during the double support phase [9]. Propulsion asymmetry was quantified as the proportion of total anterior GRF generated by the paretic leg subtracted from 0.5 and then taking the absolute value [6]. Paretic step ratio was calculated as the ratio of the paretic step length to the overall stride length [8]. To compute step length asymmetry, this number was then subtracted from 0.5 and the absolute value of the difference was taken.

The number of modules required to account for >90% of the EMG variability was found using non-negative matrix factorization previously described in detail [12]. To assess module quality, the module composition and timing for each post-stroke participant were compared to the average module composition and timing from the control group. Pearson's correlation coefficient was used to compare the composition of each module, represented by a 1×8 array of muscle weightings, between each stroke participant and the controls. Module composition quality was defined as the correlation coefficient, with 1.0 being a perfect association with the healthy group mean. The quality of module timing was assessed by calculating a timing error, defined as the difference in timing peaks of the hemiparetic modules relative to the control group as a percentage of the gait cycle. In module 3, where the module has two timing peaks, overall timing quality was calculated as the average of the two timing errors.