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Characteristics of horizontal force generation for individuals post-stroke walking against progressive resistive forces

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ABSTRACT

Background: Walking, while experiencing horizontal resistive forces, can allow researchers to assess characteristics of force generation in a task specific manner for individuals post-stroke.
Methods: Ten neurologically nonimpaired individuals (mean age 52 years) and fourteen chronic stroke survivors (mean age 54 years) with hemiparesis walked in the treadmill-based KineAssist Walking and Balance System, while experiencing twelve progressive horizontal resistive forces at their comfortable walking speed. Slope coefficients of the observed force–velocity relationship were quantified and submitted to an iterative k-means cluster analysis to test for subgroups within the post-stroke sample. Extrapolated force values for individuals were quantified by extrapolating the line of best fit of the force–velocity relationship to the x-intercept.
Findings: Within the post-stroke group, six individuals were clustered into a high sensitivity group, i.e., large reduction in speed with resistance, and eight were clustered into a low sensitive group, i.e., small reduction in speed with resistance. The low sensitivity group was similar to non-impaired individual. The extrapolated force was significantly higher for non-impaired individuals compared to individuals post-stroke in either the high or low sensitivity group. The differences between low and high sensitivity group suggest that high sensitivity of walking speed to applied resistive force is indicative of overall weakness.
Interpretation: Individuals with high sensitivity to horizontal resistive force may be walking at or near their maximum force generating capacity when at comfortable walking speed, while low sensitivity individuals may have greater reserve force generating capacity when walking at a particular comfortable walking speed.

1. Introduction

Limited locomotor ability, such as very slow walking speed, is an important factor in determining the degree of physical disability and independence for individuals post-stroke (Perry et al., 1995). Impaired force generating capacity has been suggested to be a primary cause of motor dysfunction for these individuals (Bohannon, 1991; Clark et al., 2006; Clark et al., 2010). Reduced rate of force development (Fimland et al., 2011) and decreased maximum isometric and isokinetic force output (Clark et al., 2006) has been documented and this decreased force output has been correlated to the observed walking speed of individuals post-stroke (Bohannon, 1986; Kim and Eng, 2003). Moreover, horizontal ground reaction forces, a measure of lower limb force production while walking, have been correlated with both walking speed and hemiparetic severity (Bowden et al., 2006). Collectively, these investigations provide evidence that very slow walking speed of individuals post-stroke can result from the limitations in force output capacity post-stroke.

However, individuals post-stroke are capable of expressing a greater range of walking speeds and horizontal propulsive forces, than typically observed. With respect to speed-generating capacity, in a recent investigation individuals post-stroke achieved walking speeds that were 150% greater than their maximum overground walking speed while walking on a treadmill with just a safety harness that provided no body weight support (Capo-Lugo et al., 2012). With respect to force-generating capacity, in a follow-up study, the self-selected speeds of individuals post-stroke walking against progressive horizontal resistive forces were faster than predicted if individuals were extremely limited in generating greater propulsive forces (Hurt et al., 2014). This suggests that these individuals have the capacity to generate propulsive forces necessary to walk at faster speeds.

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The task of walking requires a complex interaction of muscle moments at individual and multiple joint segments (Neptune et al., 2001; Robertson and Winter, 1980) to support the center of mass and generate forward progression. Traditional strength measures that attempt to isolate individual joint moment outputs at either isometric or isokinetic speeds may not capture the entirety of force generation impairment post-stroke. While walking, force output is quantified using fore-aft ground reaction forces and/or moment generation at individual's comfortable or maximum walking speed (Bowden et al., 2006; Milot et al., 2007). More recently, investigations have considered the observed moment generation while walking relative to dynamometric measures of maximum strength (Milot et al., 2006; Milot et al., 2007). However, these measures may not fully describe the capability of the central nervous system to generate a greater range of force in a functional manner. Walking, while experiencing horizontal resistive forces, can allow researchers to assess characteristics of force generation in a task specific manner. Although investigations have utilized this methodology to assess the relationship between mechanical and metabolic work requirements during walking (Donovan and Brooks, 1977; Gottschall and Kram, 2003); no study, to date, has utilized this methodology to characterize parameters of force generation while walking. Assessing individuals walking at their self-selected comfortable walking speed (CWS), while progressive horizontal resistance is applied, may reveal new insight into the nature of force generation impairment during walking post-stroke.

Therefore, the purpose of this study was to investigate characteristics of horizontal force generation of individuals post-stroke walking at self-selected comfortable walking speeds under progressive horizontal resistive forces in order to characterize maximum horizontal force generating capacity, compared to nonimpaired individuals. Due to the previously reported reduced force generation capacity, we hypothesized that individuals post-stroke, compared to non-impaired individuals, would demonstrate lower estimated maximum force output capability. In addition, we hypothesized that the rate of speed reduction relative to the progressively increasing horizontal force (i.e., sensitivity) will be steeper in individuals post-stroke, especially in individuals with slower CWS, due to their lack of ability to increase propulsive force proportional to the requirements of the task. This study represents the first description of a new measurement tool that can assess progressive capacity to generate propulsive force during walking post-stroke.

2. Methods

Fourteen chronic stroke survivors (>6 months post ictus; age range: 42–82; 54 SD 12 years old) with hemiplegia and 10 non-impaired individuals (age range: 41–61; 52 SD 7 years old) volunteered to participate in this institutionally reviewed and approved study. All data were collected at the Department of Physical Therapy and Human Movement Sciences at Northwestern University. Northwestern University IRB approved the study for human subject participation. The inclusion criteria of post-stroke were as follows: unilateral stroke, able to walk 10 m independently without walking aids other than ankle foot orthoses, medically stable (controlled blood pressure, no arrhythmia, and stable cardiovascular status), and can provide written informed consent. Recruitment criteria for the nonimpaired individuals were: over 40 years of age, no musculoskeletal, cardiovascular or neurological disorders that affected their gait performance, and able to walk 10 m without assistance.

Participants from the above groups were excluded when they had the following conditions: (1) severe cardiac disease (New York Heart Association classification II–IV), (2) systolic blood pressure reduction >20 mm Hg of quiet standing, resting systolic pressure >140 mm Hg and diastolic blood pressure >90 mm Hg, (3) poorly controlled or brittle diabetes mellitus history, (4) lower limb amputation history, (5) presence pre-morbid gait disorder from any cause, (6) a history of lower limb non-healing ulcer, (7) simple commands following failure, and (8) weight >113 kg (due to weight restriction of robotic device). The Berg Balance Scale and Fugl–Meyer assessments were performed on individuals post-stroke (Blum and Korner-Bitensky, 2008; Fugl-Meyer et al., 1975). Participant's characteristics are shown in Table 1. All participants provided written informed consent prior to participation in this investigation.

2.1. Experimental task

The KineAssist Gait and Balance Training System™ (HDT Global, Solon OH, USA, Fig. 1) was employed for the study (Capo-Lugo et al., 2012; Patton et al., 2007). The robotic device was stationary and connected with a Biodex-RMS treadmill (Biodex, Shirley, NY, USA) for this investigation. Individuals interacted with the robot through a pelvic harness. Embedded in the pelvic harness are bi-lateral, force transducers, which, based on a linear relationship between the measured horizontal force and treadmill belt velocity, allow the treadmill to be self-driven at a large range of speeds (0–3.0 m/s). The progressive horizontal resistive forces were generated by modifying the relationship between forces required to move the treadmill belt at a given speed. All participants were tested as follows: 1) three trials each of 10-meter walk test (10-MWT) overground at self-selected comfortable walking speed (CWS) and self-selected maximum walking speed (MWS), 2) a horizontal resistive test while walking in a robotic device, and 3) twelve progressive horizontal resistive forces walking trials that were determined from the horizontal resistive test. A tether that was anchored to the KineAssist was attached to a vest and was used to limit the forward trunk flexion to 10°. As described above, only measured force signals from transducers in the pelvic interface are used to dictate the treadmill belt speed. The tether was utilized to limit the extent that individuals could use their body weight to drive the treadmill belt. This was particularly important for high resistive force magnitudes. Participants were allowed to undergo a short familiarization process with the device.

A horizontal resistive force test preceded the progressive horizontal resistive test. Up to three trials, lasting 90 s each, were collected for each participant. Resistive force was increased every 30 s. With each trial the increasing steps of resistive force were smaller as the force level was reached in which no noticeable movement of the treadmill belt was detected. Participants were encouraged “to try your best to keep walking no matter how hard it gets” as the horizontal resistance was increased. The maximum value for each participant was then used to determine the range of resistive forces that individuals experienced for the subsequent walking trials.

Participants were then asked to walk at “the speed that feels the most comfortable” against twelve progressively increasing horizontal resistance levels. If the maximum force from the horizontal resistive force test was 120 N, twelve intervals of 10 N increments were randomly presented. In each walking trials, approximately 20 continuous steps were collected at each force interval. At least 30 s of rest was permitted between each trial.

2.2. Data processing and statistical analysis

In order to assure that we selected data from a steady-state walking condition, we used custom software (MATLAB, MathWorks, Natick, MA, USA) to determine the lowest coefficient of variation, i.e., the standard deviation of speed/the mean speed, of a moving ten second window of the treadmill belt speed over the duration of the trials to ensure that individuals were walking at a constant speed. This window of data was then used for the subsequent analysis. We utilized a simple regression to quantify the relationship between horizontal resistive force and walking speed. This presumed a negative linear relationship represented the sensitivity of individuals' comfortable walking speed to progressive horizontal resistive force. Only individuals with a significant linear fit were used for subsequent analyses. The slope coefficients were then submitted to an iterative k-means cluster analysis. This analysis was