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Mediolateral foot placement ability during ambulation in individuals with chronic post-stroke hemiplegia

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ABSTRACT

Mediolateral (ML) foot placement is an effective way to redirect the lateral trajectory of the body center of mass (BCoM) during ambulation, but has only been partly characterized in the chronic post-stroke population despite their increased risk for falling [1]. During able-bodied gait, the locomotor system coordinates lower limb swing phase kinematics such that an appropriate ML foot placement occurs upon foot contact. Muscle weakness and abnormal motor patterns may impair foot placement ability post-stroke. The purpose of this study was to characterize ML foot placement ability during post-stroke ambulation by quantifying ML foot placement accuracy and precision, for the both sound and affected feet. Age matched able-bodied individuals were recruited for comparison. All participants were instructed to target step widths ranging from 0 to 45% leg length, as marked on the laboratory floor. Results of this study confirmed that ML foot placement accuracy and precision were significantly lower for the post-stroke group as compared to the control group ($p = 0.0$). However, ML foot placement accuracy and precision were not significantly different between the affected and sound limbs in the post-stroke group. The lowest accuracy for post-stroke subjects was observed at both extreme step width targets (0 and 45%). Future work should explore potential mechanisms underlying these findings such as abnormal motor coordination, lower limb muscle strength, and abnormal swing phase movement patterns.

1. Introduction

The ability to modify mediolateral (ML) foot placement is important for safe and efficient ambulation [2,3]. ML foot placement is an effective way to redirect the ML component of the body center of mass (BCoM) trajectory during ambulation [4]. To achieve the desired foot placement at the beginning of stance phase, adjustments to the locomotor system (likely via hip ab/adduction) occur during the preceding swing phase [2]. Pathological populations (e.g., persons post-stroke) with impairments of neuromuscular functioning that affect swing phase may be unable to effectively adjust foot placement during ambulation. If ML redirection is inadequate, the ML component of BCoM may progress beyond the functional base of support (BoS), and result in instability or a fall. Therefore, the ML location of the foot is important because it establishes the general limits within which the BCoM must reside to maintain safe forward progression [1].

Stroke is the leading cause of long-term disability [5]. Hemiparesis and impaired motor coordination resulting from stroke lead to myriad abnormal gait characteristics. Specifically, abnormal ankle, knee, and hip control during swing phase may impair ML foot placement ability. While a direct link has not been established between ML foot placement ability and falls, ML foot placement is important for maintaining balance during ambulation, the task during which most falls occur in the post-stroke population [6,7].

ML foot placement ability, defined here as the accuracy and precision of targeted ML foot placements, remains uncharacterized during post-stroke locomotion. However, ML foot placement accuracy for both the affected and sound limbs of post-stroke individuals attempting mid-swing ML foot placement adjustments during supported and unsupported single-step tasks have been reported [8]. Notably, ML foot placement accuracy was lowest when subjects were unsupported and were aiming for medial targets. Accuracy increased when subjects completed the same task with an external support frame. These findings suggest that subjects may have prioritized balance, using wider foot

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placements to ensure stability, at the expense of experimental task accuracy for narrow targets [8]. Likewise, ML foot placement during ambulation may be indicative of the overall balance capabilities of the post-stroke locomotor system.

The purpose of the present study was to characterize bilateral ML foot placement ability during post-stroke gait. We defined "ability" as both the accuracy and precision (i.e., variability) of ML foot placement in response to step width targets ranging from 0 to 45% of the subject's leg length (LL). To reduce the confounding influence of acute neuromuscular recovery, we recruited individuals in the chronic phase of post-stroke recovery (defined here as at least one year post-stroke). Additionally, an age-matched convenience sample of able-bodied individuals served as a control group. We hypothesized that post-stroke individuals would have reduced ML foot placement ability with their affected foot compared to both their sound foot and controls. We hypothesized that ML foot placement ability for the affected foot of individuals post-stroke would be greatest at target step widths near their preferred step width. We did not expect ML foot placement ability to be step width dependent for the sound foot or for controls. The results of this study will contribute to our understanding of ML foot placement in persons post-stroke, an important mechanism for maintaining dynamic balance.

2. Methods

Individuals with chronic post-stroke hemiplegia were recruited from a nearby rehabilitation hospital, from a research subject database in our center, and from the surrounding community. Subjects were required to be greater than one year post-stroke, 18 years of age or older, able to understand simple instructions, and able to walk with shoes but without a cane or other assistive device for at least 12 m. Subjects were excluded if they had other comorbidities that would affect gait or could not ambulate without assistive devices. We also recruited a convenience sample of able-bodied individuals with no underlying gait-related pathologies.

The University's Institutional Review Board approved this study. Subjects provided written informed consent prior to testing. Subject-specific information recorded for all subjects included gender, age, height, weight, dominant limb, and shod foot length; and, for stroke subjects, affected side and number of years post-stroke. The target step width for each condition was based on leg length (LL) measured bilaterally from the anterior superior iliac spine (ASIS) to the ipsilateral medial malleolus with subjects in a supine position, the standard in clinical practice. If LL discrepancies were present between the limbs, an average LL was calculated. Shod foot length was measured using a Ritz stick (Woodrow Engineering Company, WI). Affected limb data for the post-stroke subjects were compared to data from the non-dominant limb of controls.

The modified Helen Hayes full-body marker set, a standard marker configuration used in clinical gait analysis [9], defined the placement of passive retro-reflective markers for kinematic data collection. Marker positions were recorded at 120 Hz with an eight-camera digital real-time motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA).

Both experimental groups were tested at the following randomized step widths: 0%, 15%, 30%, and 45% LL. For reference, able-bodied step widths are typically 12% LL [10]. Data from previous experiments in our laboratory indicate that average step width post-stroke is ~20% LL (~18.8 cm) when subjects walk at their preferred walking speed without assistive devices [11]. The range of step widths chosen for the present study was intended to challenge both subject groups at step widths narrower and wider than their preferred step width. Step widths were normalized by LL to account for the biomechanical effects of stature. Tape placed on the laboratory floor at each selected step width indicated target ML foot placement. Subjects were instructed to walk at a comfortable walking speed while placing one foot on each line or as close as possible. In addition to their preferred walking speed, control subjects were tested at a walking speed that matched the preferred walking speed of post-stroke subjects to determine if ML foot placement ability displayed speed dependent characteristics.

Laboratory personnel demonstrated the experimental task to ensure that study participants understood verbal instructions. Subjects completed six walking trials for each target step width and rested as needed throughout the experiment.

The standard marker set does not provide sufficient information to locate the perimeter of the shoe at each ML foot placement during the walking trials. Since this was necessary to categorize each ML foot placement as a success or miss, a digital representation of the outline of the shoe was created using a technique previously developed in our laboratory [12]. Following collection of the static trial, laboratory personnel traced an ink outline of each foot onto paper placed on the floor prior to data collection. Subjects stepped off the paper and laboratory personnel digitized the shoe outline by manually tracing the ink outline with a retro-reflective marker. Coordinate system transformations were used to calculate each shoe outline location during walking trials.

For the post-stroke group, six walking trials were used to calculate preferred walking. Subjects walked back and forth across a 10 m walkway at their preferred walking speed, shod but without assistive devices or step width restrictions. Following data collection, mean walking speed was calculated for the post-stroke group. Individuals whose preferred walking speed was more than two standard deviations away from the group mean were excluded from subsequent analyses.

Marker position data were smoothed using a 4th order bidirectional Butterworth filter at an effective cut-off frequency of 6 Hz [13], using Cortex software (MAC, Santa Rosa, CA, USA). Gait events were generated using OrthoTrak software (MAC, Santa Rosa, CA, USA).

Global foot outlines from the static trial were transformed into local foot coordinates using custom MATLAB® (The MathWorks Inc., Natick, MA, USA) programs. Local foot outline coordinates were calculated for each frame of the walking trial before being transformed back to global coordinates for analysis. The following criteria helped categorize results: ML foot placement was a success if it was located directly on the target line, a lateral miss if the entire foot outline was lateral to the target line, or a medial miss if the entire foot outline was medial to the target line. Thus, the frequency of successes, lateral misses, and medial misses characterized the directional bias of ML foot placement for each step width condition.

The distance between the ankle center and the target line quantified ML foot placement accuracy for each foot strike. The standard deviation of this distance for all foot strikes within a step width condition quantified ML foot placement precision.

A mixed two-way repeated measures multivariate analysis of variance (MANOVA) was used to test whether ML foot placement ability (i.e., accuracy and precision) was different between the affected foot for the post-stroke group and the non-dominant foot for the control group (the between-subjects factor = *group* [stroke/control] and the within-subject factor = *step width* [0%, 15%, 30%, and 45% LL]).

A two-way repeated measures MANOVA was used to test whether ML foot placement ability was different between the affected and sound limbs (wherein the within subjects factors = *step width* [0%, 15%, 30%, and 45% LL] and *leg* [affected/sound]). If residuals were not normally distributed or if variances were not homogeneous between the two groups, a transformation was applied.