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Biomechanical gait characteristics of naturally occurring unsuccessful foot clearance during swing in individuals with chronic stroke

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ABSTRACT

Background: Altered gait mechanics are common following stroke and may increase the risk of falls. Paretic gait impairments have been previously compared to the non-paretic limb or control participants. Unfortunately, the biomechanical parameters underlying instances of naturally occurring unsuccessful foot clearance (trips) have yet to be examined in individuals with chronic stroke.

Methods: Gait data from 26 participants with chronic stroke were obtained on a dual-belt instrumented treadmill. Instances of successful and unsuccessful foot swing were identified. Temporal, kinematic, and kinetic measures of the paretic limb occurring during late stance, toe-off, and swing were compared between trip and non-trip steps using paired samples t-tests. An $\alpha = 0.004$ was used to adjust for multiple comparisons.

Findings: In the paretic limb, the ankle angle at toe off ($P = 0.003$; $d = 0.64$), knee flexion velocity at toe off ($P < 0.001$; $d = 0.73$), and peak knee extension moment during terminal stance ($P < 0.001$; $d = 0.74$) were significantly different between trips and non-trip steps. During trip steps, ankle plantarflexion at toe-off was 1.0° greater, knee flexion velocity was reduced by 17.6 °/sec, and peak knee extension moment was increased by 0.011 Nm/kg · m compared to non-trip steps.

Interpretation: It appears to take only minor changes in the movement of the paretic limb to result in a trip in individuals with chronic stroke. Although small, the multi-joint biomechanical changes occurring in the paretic limb during unsuccessful foot clearance result in a functionally longer limb. Thus, interventions targeting multiple joints in the paretic limb may be needed to reduce the risk of trips following stroke.

1. Introduction

Falls and fall-related injuries are common complications following stroke (Forster and Young, 1995). The detrimental consequences of falls include fractures, soft tissue injury, hospitalizations, decreased mobility, and negative psychological outcomes such as increased fear and anxiety (Weerdesteyn et al., 2008). Additionally, falls after stoke are associated with poor rehabilitation outcomes, loss of independence, and chronic disability (Ramnemark et al., 2000). In individuals with chronic stroke, falls occur most often during mobility tasks such as walking and transferring from one surface to another (Forster and Young, 1995; Harris et al., 2005; Jorgensen et al., 2002; Schmid et al., 2013; Weerdesteyn et al., 2008). Due, in part, to the increased risk of falls during ambulation, improving walking ability represents a primary goal in stroke rehabilitation. Nevertheless, common gait deviations persist following stroke such as decreased walking speed, reduced foot clearance, and stance time asymmetries, which are purported to contribute to the risk of falls (Weerdesteyn et al., 2008).

Given the prevalence of falls during walking, specific gait characteristics may be related to trips and falls. Although hemiparetic gait impairments following stroke can vary considerably among individuals, paretic joint kinematic patterns often include reductions in hip, knee, and ankle flexion during swing (De Quervain et al., 1996; Mulroy et al., 2003; Olney and Richards, 1996). Lower limb kinetic alterations such as reduced hip, knee, and ankle joint moments and powers during late stance and pre-swing have also been identified (Chen and Patten, 2008; Kerrigan et al., 2001) and are related to swing phase dynamics (Goldberg et al., 2003). The net result of these paretic limb biomechanical alterations is a functionally longer limb during swing which challenges successful foot clearance. Unsuccessful foot clearance (i.e., a trip) during the swing phase of gait is important because they can contribute to falls and further injury to individuals following stroke. The biomechanical parameters underlying instances of unsuccessful foot clearance have yet to be examined. Our aim is to examine the parameters leading to *naturally occurring trips* during ambulation. This experimental design is notably different than previous studies that induced trips via perturbations or unexpected obstacles (Owings et al., 2001;

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Smith et al., 2000) or compared the gait of fallers to non-fallers (Guimaraes and Isaacs, 1980).

The purpose of this study is to determine the spatiotemporal, kinematic, and kinetic characteristics of the paretic lower extremity associated with naturally occurring unsuccessful foot clearance in participants with chronic hemiparesis secondary to stroke. We hypothesized that participants will exhibit biomechanical alterations during late stance, consistent with the production of a functionally longer paretic limb in swing phase. The paretic leg posture we expected to see during trips, compared to instances of successful foot clearance, included increased hip extension during late stance, decreased knee flexion velocity at toe-off, and increased ankle plantarflexion at toe-off. Likewise, we expected to see joint kinetic alterations consistent with increased limb extension (i.e., reduced hip flexion moment, increased knee extension moment during late stance). By exploring potential patterns demonstrated during trips, we can design targeted interventions to improve walking ability and decrease falls post-stroke.

2. Methods

2.1. Participants

We evaluated data from 40 participants with chronic (>6 months) hemiparesis secondary to stroke who participated in parts of a larger study examining gait kinematics and kinetics during treadmill ambulation (Feasel et al., 2011; Rhea et al., 2012). All participants exhibited clinical symptoms consistent with an ischemic or hemorrhagic unilateral brain lesion, resulting in sensory motor dysfunction more than 6 months prior to recruitment. Stroke was determined via self-report and confirmed by a physician while receiving medical clearance for study participation. Participants were excluded if they exhibited additional neurologic (e.g., Parkinson's disease, vestibular disorders), musculoskeletal, or cardiovascular pathology that would preclude treadmill walking, or had a history of balance deficits or falls unrelated to the stroke. Participants who required an ankle foot orthosis (AFO) for safe ambulation were also excluded from this analysis due to the imposed alterations in lower limb joint mechanics from the AFO. Twenty-six participants who demonstrated unsuccessful foot clearance during training on the treadmill were analyzed here. All participants signed an informed consent form which was approved by the IRB at UNC Chapel Hill.

2.2. Data collection

Gait data for each participant were obtained from a 20 minute treadmill walking session on a dual-belt 'instrumented' treadmill (Bertec Corp., Columbus, OH, USA). Treadmill speed was chosen for each participant by a physical therapist as the speed that the participant could maintain for the duration of the training session, with the goal of a heart rate of 70% of max or RPE of 14 on the Borg scale. All participants wore a harness attached overhead while walking, which did not provide unweighting or restrict lower limb movement. Participants did not use assistive devices during training and no manual facilitation was provided to alter participants' gait patterns. A handrail was available for participants to hold onto, although they were discouraged from doing so. Although participants were exposed to either a virtual environment (Feasel et al., 2011) or variable belt speeds (Rhea et al., 2012) during other test sessions, we only used data acquired from 'control' sessions, when virtual environments were off and treadmill belts were moving at a constant speed.

While walking on the treadmill, lower extremity and pelvic movement data were recorded in three-dimensional space using an 8-camera motion capture system (Vicon, Denver, CO, USA) at 120 Hz, as ground reaction forces (GRFs) were sampled concurrently at 960 Hz from both sides of the treadmill. Limb segments were tracked with retroreflective markers taped to the participant's pelvis, legs, and feet. Details describing marker placement setup have been previously described (Murray et al., 2014). Visual3D software (C-Motion, Germantown, MD, USA) was used to model the three-dimensional motion of the pelvis and lower limb segments. Marker trajectories and GRF data were low-pass filtered at 6 and 20 Hz, respectively. Hip, knee, and ankle joint angles were computed using Euler angles, and internal joint moments were computed using an inverse dynamics approach. All joint moments were normalized to subject mass and height.

2.3. Data management

All instances of unsuccessful foot clearance (defined here as a trip) during the 20 minute treadmill walking session were initially identified. These trips were identified by the presence of a vertical GRF which exceeded 10 N on the paretic limb's treadmill belt during its respective swing phase (see Fig. 1). We then identified the stride immediately prior to each trip (i.e., which did not contain a trip) and labeled it as an instance of successful foot swing. For participants demonstrating a large number of trips during the training session, a maximum of 15 steps were used for analysis.

Spatiotemporal, kinetic, and kinematic variables were calculated for each labeled step using custom written LabVIEW software (National Instruments, Austin, TX, USA). Because we were interested in the biomechanics influencing the swing phase dynamics of the paretic limb, we focused our data collection on the late stance, toe-off, and swing phases of the gait cycle. The spatiotemporal measure of interest was double support time (non-paretic heel strike to paretic toe-off in milliseconds). Pre-swing kinematic measures included peak hip extension angle during late stance, knee flexion velocity at toe-off, and ankle angle at toe-off. Swing-phase kinematic measures included peak knee and ankle flexion angles and circumduction (frontal plane excursion of the swing foot with respect to the stance foot). Kinetic measures included the propulsive impulse and the peak hip flexion, knee extension, and ankle plantarflexion moments during late stance. Outcome measures of successful and unsuccessful foot clearance were then averaged for each participant.

2.4. Data analysis

Within-subject statistical analyses were performed for each outcome variable using SPSS, ver 16 (SPSS, Chicago, IL, USA). Paired-samples t-tests were used to compare outcome measures between instances of successful and unsuccessful foot clearance. Adjustments for multiple comparisons were performed by reducing the alpha level

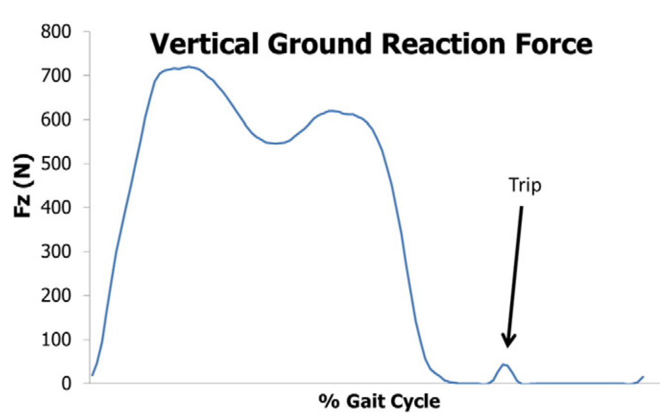

Fig. 1. Representative vertical ground reaction force illustrating instance of 'trip' during swing phase. The trip is identified by the presence of a ground reaction force that exceeds 10 N during swing (marked with an arrow).