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Biomechanical variables related to walking performance 6-months following post-stroke rehabilitation

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ABSTRACT

Background: Body-weight supported treadmill training has been shown to be effective in improving walking speed in post-stroke hemiparetic subjects, and those that have shown improvements generally maintain them after the completion of rehabilitation. However, currently no biomechanical variables are known to be related to those who will either continue to improve or regress in their self-selected walking speed during the 6-month period following rehabilitation. The objective of this study was to identify those biomechanical variables that are associated with subjects who continue (or did not continue) to improve their self-selected walking speed following the completion of rehabilitation.
Methods: Experimental kinematic and kinetic data were recorded from 18 hemiparetic subjects who participated in a 6-month follow-up study after completing a 12-week locomotor training program that included stepping on a treadmill with partial body weight support and manual assistance. Pearson correlation coefficients were used to determine which biomechanical variables evaluated during the post-training session were related to changes in self-selected walking speed from post-training to a 6-month follow-up session.
Findings: Following the completion of rehabilitation, the majority of subjects increased or retained (i.e., did not change) their self-selected walking speed from post-training to the follow-up session. Post-training step length symmetry and daily step activity were positively related to walking speed improvements.
Interpretation: Motor control deficits that lead to persistent step length asymmetry and low daily step activity at the end of rehabilitation are associated with poorer outcomes six months after completion of the program.

1. Introduction

Persons with post-stroke hemiparesis often exhibit a reduced self-selected walking speed relative to healthy subjects (Olney and Richards, 1996). Improving walking ability is a common goal for post-stroke hemiparetic subjects (Bohannon et al., 1988) and often the primary goal of rehabilitation programs. Body-weight supported treadmill training (BWSTT) has been shown to be effective in improving post-stroke hemiparetic walking ability as measured by self-selected walking speed (Duncan et al., 2011; Hesse et al., 1995; Mulroy et al., 2010; Peurala et al., 2005; Plummer et al., 2007; Sullivan et al., 2007; Visintin et al., 1998). Previous studies have shown that most improvements in walking speed are maintained three to six months after the completion of training (Duncan et al., 2011; Peurala et al., 2005; Sullivan et al., 2007; Visintin et al., 1998). A recent clinical trial with a large number of subjects (n = 408) found that gains were maintained 12 months post-stroke (Duncan et al., 2011). While subjects as a group tend to retain their gains, no study has investigated whether specific biomechanical variables exist that are associated with subjects achieving further speed improvements or regressing toward their pre-training speed following rehabilitation. Quantities such as joint kinetics, spatiotemporal variables or daily step activity may be able to identify those subjects who retain or improve their walking speed following rehabilitation.

Ankle plantarflexor function may be such an identifier, as the ankle plantarflexors have been found to be the primary contributors to forward propulsion and critical for increasing walking speed in healthy walking (Liu et al., 2008; Neptune et al., 2008). However, paretic leg plantarflexor weakness is a primary impairment in post-stroke hemiparetic walking (Nadeau et al., 1999). Modeling and simulation studies of hemiparetic walking have shown that the paretic leg plantarflexors have reduced contributions to forward propulsion compared to control subjects walking at similar speeds (Peterson et al., 2010), and that the reduced contributions limit walking speed post-stroke (Hall et al., 2011). Conversely, others have shown that hemiparetic subjects who

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improve their walking speed with rehabilitation increase paretic leg ankle plantarflexor power (Mulroy et al., 2010; Parvataneni et al., 2007; Teixeira-Salmela et al., 2001). Thus, plantarflexor output may be associated with further speed increases following rehabilitation.

Studies have also suggested that the paretic leg hip flexors may compensate for plantarflexor weakness in some hemiparetic subjects (Nadeau et al., 1999; Olney and Richards, 1996). In addition, hemiparetic subjects have increased hip flexor power output after rehabilitation with increased walking speed (Mulroy et al., 2010; Parvataneni et al., 2007; Teixeira-Salmela et al., 2001). Modeling and simulation studies of healthy walking have shown that the uniarticular hip flexors provide swing initiation together with the gastrocnemius (e.g., Neptune et al., 2008). Thus, improved swing initiation provided by the paretic leg hip flexors will advance the paretic leg forward and increase the paretic leg step length, and therefore potentially improve walking speed.

In addition, subjects with hemiparesis typically generate asymmetric paretic and non-paretic leg anterior–posterior ground reaction forces (AP GRFs) during walking, which will directly influence walking speed. Bowden et al. (2006) showed that propulsion symmetry and the paretic leg propulsive impulse (i.e., time integral of the paretic leg propulsive AP GRF) were both positively correlated with hemiparetic severity (as defined by Brunnstrom stages) and walking speed. Therefore, propulsion generation may be associated with subjects who continue to improve their walking speed following rehabilitation.

Similarly, persons with post-stroke hemiparesis walk with asymmetrical step lengths with the direction of asymmetry varying between subjects (Balasubramanian et al., 2007). Step length asymmetry has been shown to be negatively related to self-selected walking speed (Balasubramanian et al., 2007; Patterson et al., 2010) and hemiparetic severity (as defined by Brunnstrom stages) (Balasubramanian et al., 2007) and to be indicative of compensatory mechanisms used by hemiparetic walkers (Allen et al., 2011).

Another measure that may be associated with walking speed outcomes is daily step activity, which has been shown to effectively quantify levels of physical activity in the home and community in hemiparetic subjects (e.g., Shaughnessy et al., 2005). A recent study showed that daily step activity positively correlates with self-selected walking speed and can differentiate hemiparetic severity (as defined by walking speed) (Bowden et al., 2008). In the rehabilitation setting, the number of repetitions has a strong positive association with successful outcomes (Birkenmeier et al., 2010). Daily step activity might similarly represent the repetition of a newly acquired walking pattern learned during rehabilitation training (with lower amounts of stepping being associated with less repetition of the training associated changes). Thus, daily step activity may be related to walking performance following the completion of rehabilitation.

The goal of this study was to assess whether any of these biomechanical variables are related to changes in self-selected walking speed following post-stroke rehabilitation. Specifically, we analyzed joint moment impulses (i.e., time integral of the joint moment), step length asymmetry, AP GRF impulses (i.e., time integral of the AP GRF) and daily step activity at the end of a 12-week rehabilitation program. We expected the paretic leg ankle plantarflexor moment impulse, paretic leg hip flexor moment impulse, step length asymmetry, paretic leg AP GRF impulse, and daily step activity to be related to successful post-stroke rehabilitation, which we define as further improvements in self-selected walking speed at a 6-month follow-up session relative to the post-training speed. By identifying those biomechanical variables that relate to further improvements in self-selected walking speed over a 6-month follow-up period, this study will help guide future locomotor training strategies to improve rehabilitation outcomes.

2. Methods

2.1. Subjects

A subset of 18 hemiparetic subjects (14 left hemiparesis; 14 men; age: mean = 58.6 years (SD = 10.9 years); time since stroke: mean = 19.9 months (SD = 15.5 months)) from a larger study at the VA Brain Rehabilitation Research Center (Gainesville, FL, USA) participated in a 6-month follow-up study after completing a 12-week locomotor training program. Inclusion criteria for entrance into the training program included a stroke within the past 6 months — 5 years, residual paresis in the lower extremity (Fugl-Meyer LE motor score < 34, Fugl-Meyer et al., 1975), ability to sit unsupported for 30 s, ability to walk at least 10 feet with maximum one person assist, self-selected 10-meter gait speed less than 0.8 m/s, and ability to follow a three step command. All subjects passed an exercise tolerance test (Yates et al., 2004) to screen for cardiovascular fitness and exercise safety prior to participation. Data from 21 age-matched control subjects (4 men; age: mean = 65.2 years (SD = 9.6 years)) were also used in this study for comparison to the hemiparetic subjects. All subjects provided written informed consent approved by the Institutional Review Boards of the University of Florida and the University of Texas at Austin.

2.2. Training program

Hemiparetic subjects participated in a 12-week locomotor training program consisting of training sessions three times a week. During each session, subjects participated in 20 min of stepping on a treadmill with partial body weight support (BWS) (Hesse et al., 1995; Plummer et al., 2007; Visintin et al., 1998) followed by 20 min of immediate translation of skills acquired during treadmill walking to overground walking. Training began with 40% BWS and progressed as tolerated to minimal BWS. Treadmill stepping took place at ~0.9–1.3 m/s with manual assistance provided by physical therapists at the hip and/or lower legs to approximate desired trunk, pelvis and lower limb kinematics and the spatiotemporal pattern of walking (Plummer et al., 2007).

2.3. Data collection

Self-selected overground walking speed was measured as each hemiparetic subject completed two trials walking across a 4.3-meter GAITRite portable walkway system (CIR Systems, Inc., Clifton, NJ, USA) at the pre-training, post-training and 6-month follow-up sessions. During each session, the hemiparetic subjects also walked at their current self-selected treadmill walking speed on a split-belt instrumented treadmill (Tecmachine, Andrézieux Bouthéon, France) while kinematic and GRF data were collected for 30 s. Only kinematic and GRF data collected at the post-training session were analyzed in this study. Each control subject walked at 0.3, 0.6 and 0.9 m/s for speed-matched comparisons. All subjects wore a safety harness mounted to the laboratory ceiling to protect against a loss of balance (no body weight was offloaded by the harness). A physical therapist was present for all data collection sessions. A 12-camera motion capture system (Vicon Motion Capture Systems, Oxford, UK) was used to record kinematics from a modified Helen Hayes marker set with rigid clusters on the pelvis and each thigh, shank and foot segments. Marker trajectories and bilateral GRF data were collected at 100 and 2000 Hz, respectively. Daily step activity data were collected for 15 of the 18 hemiparetic subjects post-training. Subjects wore a StepWatch™ Activity Monitor (Orthocare Innovations, Washington, DC, USA) for 4 days to calculate the average number of steps per day in the home and community.

2.4. Data analysis

Data were processed using Visual3D (C-Motion, Inc., Germantown, MD, USA). Intersegmental joint moments (normalized by body mass) were calculated using standard 3D inverse dynamics techniques for the data collected during the post-training session. GRF data were normalized by body weight. All data were time normalized to 100% of the paretic leg gait cycle for the hemiparetic subjects and to the right leg gait cycle for the control subjects. The typical propulsive regions of the ipsilateral gait cycle were divided into late single-leg stance (i.e., second 50% of single-leg stance) and pre-swing (i.e., double support region preceding toe-off) regions. Sagittal plane hip (flexor positive), knee (extensor positive) and ankle (plantarflexor positive) joint moment impulses and the AP GRF impulse (AP impulse) were calculated in each region. For the control subjects, the impulses for both legs were averaged and data from all control subjects were averaged at each walking speed (0.3, 0.6 and 0.9 m/s). The impulses for the hemiparetic subjects were normalized by the control data at matched speeds according to functional walking status (Perry et al., 1995) (Table 1). Step length symmetry (Paretic Step Ratio, PSR = paretic step length/(paretic + non-paretic step length)) and propulsion symmetry (Paretic Propulsion, PP = paretic AP impulse/(paretic + non-paretic AP impulse)) were also calculated for each subject. To account for variations from symmetry (0.5), the absolute value of the deviation from 0.5 was calculated for the PSR and PP quantities. A speed ratio was calculated for each subject to indicate relative changes in self-selected overground walking speed from post-training to follow-up sessions (i.e., follow-up speed/post-training speed). Speed ratios between 0.9 and 1.1 were considered to indicate no relative change in speed between sessions (Beaman et al., 2010). Pearson correlation coefficients were calculated using MATLAB (Mathworks, Natick, MA, USA) between the speed ratio and the various biomechanical variables (joint moment and AP impulses, daily step activity, self-selected overground walking speed, PSR and PP) at the post-training session with a significance level of 0.05.

3. Results

The average self-selected overground walking speed for the hemiparetic subjects was 0.52 m/s (SD = 0.20 m/s), 0.72 m/s (SD = 0.26 m/s) and 0.74 m/s (SD = 0.28 m/s) at the pre-training, post-training and follow-up sessions, respectively (Table 2). Twelve hemiparetic subjects had a clinically meaningful increase in self-selected walking speed from pre- to post-training (i.e., change ≥ 0.16 m/s, Tilson et al., 2010) (Table 2). Five subjects increased walking speed (speed ratio > 1.1), eleven subjects had no relative change in speed (0.9 ≤ speed ratio ≤ 1.1) and two subjects decreased walking speed (speed ratio < 0.9) from post-training to their 6-month follow-up session (Table 2). PSR was negatively related with the speed ratio ($P = 0.014$) and PP was not related to the speed ratio (Table 3, Fig. 1). While daily step activity was positively related to the speed ratio ($P = 0.042$), post-training self-selected overground walking speed was not related to the speed ratio ($P = 0.422$) (Table 3, Fig. 1).

3.1. Relationships with the speed ratio during the late single-limb stance region

During the respective late single limb-stance regions, there were no relationships between paretic and non-paretic leg joint moment impulses and the speed ratio (Table 3, Fig. 2). Also, the paretic and non-paretic leg AP impulses were not related to the speed ratio during the respective late single-limb stance regions (Table 3, Fig. 2).

Table 1
Joint moment and AP impulse data for the hemiparetic subjects were normalized by average control data at matched speeds based on functional walking status (Perry et al., 1995).

Functional walking status	Hemiparetic self-selected walking speed (m/s)	Control walking speed (m/s)
Household	<0.4	0.3
Limited community	0.4–0.8	0.6
Community	>0.8	0.9

Table 2
Overground self-selected walking speed at the pre-training, post-training and follow-up sessions for the hemiparetic subjects. Speed ratios were calculated as follow-up/post-training speed. Step length symmetry (PSR) and daily step activity at the post-training session for the hemiparetic subjects. Note that daily step activity data were collected for 15 of the 18 hemiparetic subjects. Subjects who had a change in self-selected walking speed from pre- to post-training that was determined to be clinically meaningful (change ≥ 0.16 m/s, Tilson et al., 2010) are indicated by *.

Subject	Pre-training speed (m/s)	Post-training speed (m/s)	Follow-up speed (m/s)	Speed ratio	PSR	Daily step activity (steps per day)
1	0.68	0.80	0.95	1.19	0.013	3973
2	0.71	0.79	0.76	0.96	0.022	1497
3	0.79	1.05*	0.99	0.94	0.013	3152
4	0.76	1.08*	1.06	0.99	0.007	2409
5	0.35	0.64*	0.61	0.96	0.007	1367
6	0.76	0.93*	0.97	1.05	0.038	1281
7	0.43	0.59*	0.49	0.83	0.081	1687
8	0.39	1.00*	1.11	1.11	0.033	4245
9	0.46	0.39	0.41	1.04	0.023	–
10	0.18	0.35*	0.24	0.68	0.175	441
11	0.29	0.31	0.31	0.99	0.142	1094
12	0.50	0.75*	0.87	1.17	0.006	1718
13	0.44	0.59	0.70	1.18	0.041	–
14	0.63	0.82*	0.80	0.98	0.015	2591
15	0.20	0.33	0.43	1.30	0.046	–
16	0.60	0.96*	0.89	0.93	0.046	2186
17	0.70	0.99*	1.09	1.10	0.008	3080
18	0.43	0.59*	0.56	0.96	0.038	5211
Average	**0.52**	**0.72**	**0.74**			
Standard deviation	**0.20**	**0.26**	**0.28**			

Table 3
Correlations of post-training joint moment impulses, AP impulses, PSR, PP, daily step activity and self-selected overground walking speed with the speed ratios (follow-up/post-training speed) for all hemiparetic subjects. The joint moment and AP impulses for the hemiparetic subjects were normalized by the average control data at matched speeds according to functional walking status. Significant correlations are indicated in bold font ($P < 0.05$).

	r	*P*
PP	−0.338	0.085
PSR	**−0.519**	**0.014**
Daily step activity (steps per day)	**0.461**	**0.042**
Self-selected overground walking speed (m/s)	0.050	0.422
Late single-limb stance region		
Joint moment impulses		
Paretic leg hip	0.380	0.060
Paretic leg knee	−0.313	0.103
Paretic leg ankle	0.039	0.439
Non-paretic leg hip	0.343	0.082
Non-paretic leg knee	0.184	0.240
Non-paretic leg ankle	0.127	0.307
AP impulses		
Paretic leg	0.233	0.176
Non-paretic leg	0.172	0.247
Pre-swing region		
Joint moment impulses		
Paretic leg hip	0.344	0.081
Paretic leg knee	−0.196	0.225
Paretic leg ankle	0.074	0.386
Non-paretic leg hip	0.254	0.154
Non-paretic leg knee	0.032	0.451
Non-paretic leg ankle	0.004	0.494
AP impulses		
Paretic leg	0.348	0.079
Non-paretic leg	−0.016	0.475

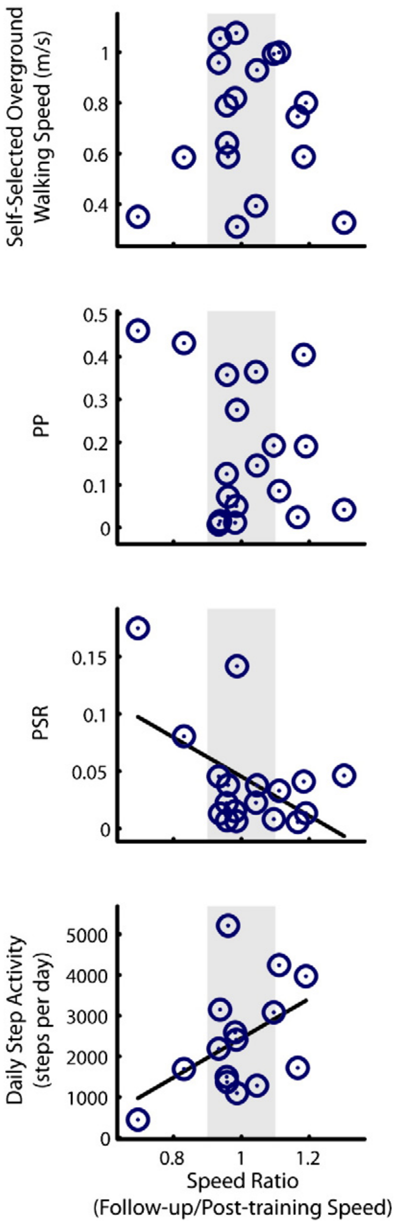

Fig. 1. Post-training self-selected overground walking speed, paretic propulsion symmetry (PP), step length symmetry (PSR) and daily step activity versus the speed ratio (follow-up/post-training speed) for all hemiparetic subjects. Note that daily step activity data were collected from 15 of the 18 hemiparetic subjects. Shaded areas represent speed ratios between 0.9 and 1.1 and indicate no relative change in speed from post-training to follow-up sessions. The linear trend line is included for significant correlations.

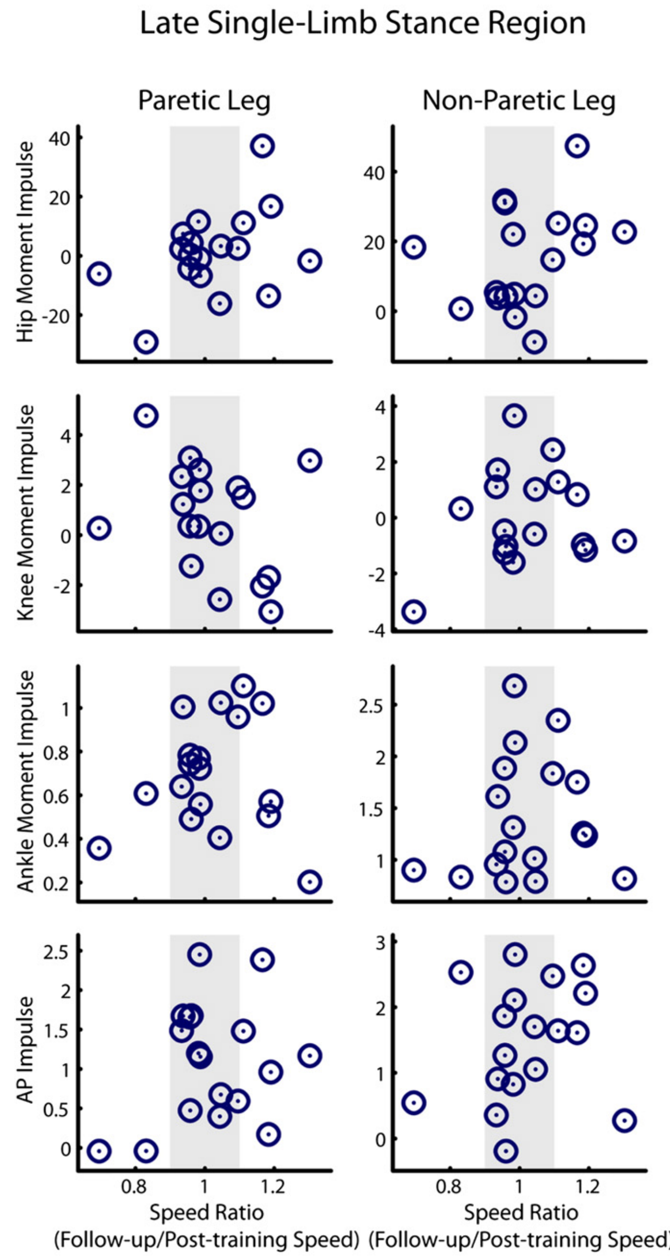

Fig. 2. Post-training joint moment and anterior–posterior (AP) impulses versus speed ratio (follow-up/post-training speed) for all hemiparetic subjects during the late single-limb stance region. The joint moment and AP impulses for the hemiparetic subjects were normalized by the average control data at matched speeds according to functional walking status. Shaded areas represent speed ratios between 0.9 and 1.1 and indicate no relative change in speed from post-training to follow-up sessions.

3.2. Relationships with the speed ratio during the pre-swing region

There were no paretic and non-paretic leg joint moment impulse relationships with the speed ratio during the respective pre-swing regions (Table 3, Fig. 3). Similarly, there were no relationships between the paretic and non-paretic AP impulses and the speed ratio during the respective pre-swing regions (Table 3, Fig. 3).

4. Discussion

While we found, like others (Duncan et al., 2011; Peurala et al., 2005; Sullivan et al., 2007; Visintin et al., 1998), that post-training gains in walking speed were retained at follow-up, we also found that speed changes between the end of training and follow-up were unrelated to whether or not a subject had attained a clinically meaningful increase in self-selected walking speed (change ≥ 0.16 m/s, Tilson et al., 2010) from pre- to post-training or their post-training walking speed. While the majority of subjects (12 of 18) had an increase in self-selected walking speed (change ≥ 0.16 m/s, Tilson et al., 2010) from pre- to post-training, their performance at follow-up was quite varied with speed ratios ranging from 0.68 to 1.17 (Table 2). Even though the remaining subjects (6 of 18) did not have a clinically meaningful increase their self-selected walking speed, speed ratios ranged from 0.96 to 1.30 and 3 of the 6 were among the subjects with speed ratios > 1.1 (Table 2). Thus, an interesting finding was that achieving clinically meaningful changes in self-selected walking speed from pre- to post-training was not necessary to improve walking speed at follow-up (i.e., speed ratio > 1.1),

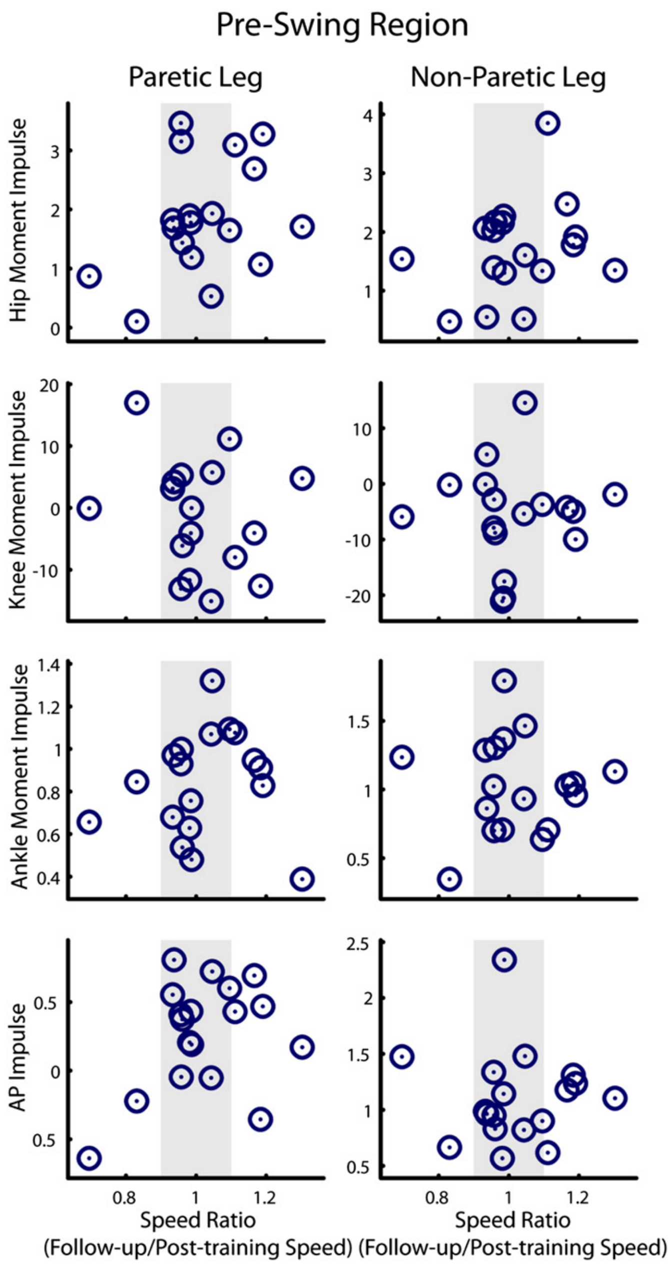

Fig. 3. Post-training joint moment and anterior–posterior (AP) impulses versus speed ratio (follow-up/post-training speed) for all hemiparetic subjects during the pre-swing region. The joint moment and AP impulses for the hemiparetic subjects were normalized by the average control data at matched speeds according to functional walking status. Shaded areas represent speed ratios between 0.9 and 1.1 and indicate no relative change in speed from post-training to follow-up sessions.

suggesting that the long-term effectiveness of rehabilitation training cannot be determined by changes in self-selected walking speed at the end of training. Specifically, three subjects whose improvements were not clinically meaningful from pre- to post-training did exceed that threshold at follow-up (all also had speed ratios > 1.1). Three other subjects who had originally achieved clinical meaningfulness at post-training were no longer at that level at follow-up, and not surprisingly they included the two subjects who had speed ratios < 0.9. The majority of subjects (16 of 18) increased or did not change self-selected walking speed from post-training to the follow-up session (Table 2), indicating that the effects of BWSTT are maintained following training. This result is consistent with previous studies that showed subjects maintained self-selected walking speed three to six months after completion of BWSTT (Duncan et al., 2011; Peurala et al., 2005; Sullivan et al., 2007; Visintin et al., 1998).

Post-training PSR was negatively related to the walking speed ratio (Table 3, Fig. 1). The negative relationship suggests that subjects with symmetric paretic and non-paretic steps had higher speed ratios than subjects with asymmetric step lengths. Previous studies have shown that hemiparetic subjects with asymmetric step lengths have lower self-selected walking speed than those with symmetric step lengths (Balasubramanian et al., 2007; Patterson et al., 2010). Our findings build upon this result and suggest that a relationship exists between step length asymmetry and changes in speed following training. Thus, it appears that if a person has motor control deficits that lead to persistent asymmetry, a locomotor training program focused on normalizing kinematics, such as in this study, may have less long-term carryover of changes in walking speed. This persistent asymmetric group may have benefited from adjunctive therapies that target the underlying motor control deficits producing the asymmetry.

Daily step activity measured at post-training had a positive relationship with the speed ratio ($P = 0.042$) (Table 3, Fig. 1), indicating that subjects who took more steps per day tended to increase walking speed from post-training to follow-up sessions. Since the number of repetitions has a strong positive association with successful rehabilitation outcomes (Birkenmeier et al., 2010), it might be expected that there would be a relationship between daily stepping (repetition of their newly acquired walking pattern) and further changes in walking speed. High step activity means more repetitions, a critical component to long term gains such that those who were able to best "practice" on their own (i.e., increase community stepping) may continue to improve. This is conceptually similar to the threshold theory for upper extremity rehabilitation (e.g., Schweighofer et al., 2009) and in animal models (MacLellan et al., 2011). It is surprising that there was a significant relationship between daily step activity and the speed ratio, but there was no relationship between post-training self-selected overground walking speed and the speed ratio. While daily step activity and walking speed are strongly related in cross-sectional studies (Bowden et al., 2008; Shaughnessy et al., 2005), this relationship has not been investigated in subjects who have just completed a rehabilitation program.

We expected that the paretic leg ankle plantarflexor moment impulse, hip flexor moment impulse and AP impulse would be significantly related to success following rehabilitation. However, the impulses during the late single-limb stance and pre-swing regions were not significantly related to the speed ratio. The lack of significant relationships between the impulses and the speed ratio suggests that the hemiparetic subjects developed a variety of compensatory strategies during rehabilitation and no single strategy (e.g., ankle vs. hip strategy) was strongly related to success following completion of rehabilitation training. The global measures of step length symmetry and daily step activity had stronger relationships with success following rehabilitation. Other measures that represent overall coordination rather than specific compensatory strategies may provide further insight into the success of hemiparetic patients following rehabilitation. In addition, other factors such as daily activity and exercise between the post-training and follow-up sessions, which we did not measure, may contribute to the observed changes in gait speed following the completion of rehabilitation.

A potential limitation of this study is that we analyzed correlations between joint moment and AP impulses measured while subjects walked on a treadmill and the speed ratio generated from overground self-selected speed measurements. Although the hemiparetic subjects did generally walk slower on the treadmill than overground, the use of overground speed measurements for the speed ratio was justified as it more closely represents the subjects' walking ability in the community. In addition, the use of an instrumented treadmill allowed for data collection to include a large number of gait cycles for a steady-state walking pattern, which is difficult to achieve during overground walking in the hemiparetic population, and we have previously found treadmill walking to reveal similar motor control deficits to those seen walking overground (Kautz et al., 2011). Another potential limitation was the differences in gender distribution between the hemiparetic (14 men) and control (4 men) groups, which may have affected the joint moment impulses. However, the joint moments were normalized by body mass which has been shown to reduce differences in peak joint moments between genders (Moisio et al., 2003). In addition, the joint moment impulses were compared between males and females in the control group at each walking speed (0.3, 0.6 and 0.9 m/s) and trends across subjects were similar for each walking speed. Therefore, we do not believe that the gender differences between the hemiparetic and control groups affected the conclusions of this study. Finally, our small sample size and large variability across subjects led to wide confidence intervals in our statistical results, and therefore caution should be taken when interpreting these findings. Future work examining a larger dataset would allow us to assess the applicability of these results to a wider hemiparetic population.

5. Conclusion

This study sought to identify biomechanical variables that relate to changes in walking ability as measured by changes in self-selected walking speed in hemiparetic subjects after completion of a locomotor rehabilitation program. The relationship between step length asymmetry and changes in walking speed suggests that subjects who had symmetric paretic and non-paretic step lengths post-training tended to continue to increase speed following rehabilitation. In addition, subjects who had higher daily step activity at the end of training also tended to continue to increase speed following rehabilitation, perhaps due to the increased number of repetitions of their newly acquired walking pattern. There was, however, no relationship between post-training self-selected overground walking speed and increased speed at follow-up. Thus, improved step length symmetry and increased daily step counts are related to improved rehabilitation outcomes, even after completion of the program. Conversely, motor control deficits that lead to persistent asymmetry and low daily step activity at the end of rehabilitation are associated with poorer outcomes.

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