

## Relationship Between Step Length Asymmetry and Walking Performance in Subjects With Chronic Hemiparesis

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**ABSTRACT.** Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis. *Arch Phys Med Rehabil* 2007;88:43-9.

**Objective:** To understand the relationship between step length asymmetry and hemiparetic walking performance.

**Design:** Descriptive.

**Setting:** Gait analysis laboratory.

**Participants:** Convenience sample of 49 subjects with chronic hemiparesis.

**Interventions:** Not applicable.

**Main Outcome Measures:** Subjects walked at their self-selected walking speed over both an instrumented mat and forceplates to collect spatiotemporal parameters and ground reaction forces, respectively. Step length asymmetry was quantified by using a step length ratio (SLR) defined as paretic step length divided by nonparetic step length. Paretic leg propulsion, self-selected walking speed, hemiparetic severity (assessed by Brunnstrom stages of motor recovery), and some spatiotemporal walking parameters quantified the hemiparetic walking performance. Paretic leg propulsion was quantified by the paretic propulsion ( $P_p$ ) ratio, calculated as the percentage contribution of paretic leg to the total propulsive impulse.

**Results:** Significant negative correlation ( $r = -.78$ ) was revealed between SLR and  $P_p$ , indicating that subjects generating less propulsive force with the paretic leg walked asymmetrically with longer paretic steps than nonparetic steps. SLR and self-selected walking speed revealed a weaker correlation ( $r = -.35$ ), whereas hemiparetic severity correlated strongly with SLR ( $\rho = -.53$ ).

**Conclusions:** Step length asymmetry is related to propulsive force generation during hemiparetic walking. Subjects generating least paretic propulsion walk with relatively longer paretic steps. This suggests that one of the mechanisms for the longer paretic step may be the relatively greater compensatory nonparetic leg propulsion. Further, those with more severe hemiparesis (those dependent on abnormal flexor and extensor synergies) walk with the longest paretic steps relative to non-

paretic. Finally, our results indicated that asymmetrical step lengths may not necessarily limit the self-selected walking speed, likely due to other compensatory mechanisms.

**Key Words:** Hemiparesis; Rehabilitation; Walking.

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**T**HE ASYMMETRICAL NATURE of hemiparetic walking is well documented in persons who have sustained a stroke,<sup>1,2</sup> with the asymmetries in spatiotemporal, kinematic, and kinetic parameters of walking related to disturbances in motor coordination.<sup>3</sup> Specifically, asymmetry in spatiotemporal parameters has been commonly used in the clinic to examine the walking patterns in patients who have experienced a stroke.<sup>4</sup> Previous studies<sup>1,5</sup> have reported that temporal (swing time) asymmetry is a significant predictor of hemiparetic walking performance, because it strongly correlates with stages of motor recovery, walking speed, and falls. However, the relationship between spatial (step length) asymmetry and hemiparetic walking performance is unclear.

It has been reported that, after a stroke, patients may walk with either relatively longer paretic or nonparetic steps.<sup>4,6,7</sup> Therefore, consistent patterns of step length asymmetry have not been observed. Moreover, the reasons for the variability in step length asymmetry and the relation of the variable patterns with walking performance have not yet been explained. For instance, in the study by Kim and Eng,<sup>4</sup> considerable variability in step length asymmetry was observed in a sample of 28 chronic stroke survivors. While 14 of these subjects walked with longer paretic steps than nonparetic, 14 others walked with relatively longer nonparetic steps. Consequently, they hypothesized that the variability in the patterns of step length asymmetry may be due to compensatory strategies that increase or decrease the step length of either the paretic or nonparetic leg. However, they were unable to advance the discussion because they found a nonsignificant relationship between step length symmetry and symmetry in vertical ground reaction forces. Further, other studies indicate that on an average, persons who have sustained a stroke walk with relatively longer paretic steps.<sup>6,7</sup> Therefore, neither consistent patterns of step length asymmetry have been observed nor have the asymmetrical patterns been characterized. Further, the relationship between step length asymmetry and walking speed is not well documented. For example, shorter stride lengths (bilaterally) have been related to slower walking speed and thereby poor walking performance,<sup>8</sup> and yet a nonsignificant relationship has been suggested between step length asymmetry and walking speed.<sup>4</sup> Overall, current evidence suggests that persons after a stroke may walk with different patterns of step length asymmetry that may be unrelated to the attained walking speed. However, it is not clear how the different asymmetrical patterns relate to poststroke hemiparetic walking performance and why asymmetry in step lengths may not necessarily limit the attained walking speed.

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We propose that correlating the asymmetry observed in step lengths with propulsive ground reaction forces during walking can provide a basis to evaluate different asymmetrical patterns in poststroke hemiparetic walking performance. Propulsive ground reaction forces represent the net forces generated by the legs to accelerate (propel) the body's center of mass (COM) forward. The propulsive ground reaction forces quantify forward propulsion during walking, which is an essential requirement of locomotion along with body support.<sup>9</sup> In our recent work,<sup>10</sup> we have shown that the paretic leg propulsive ground reaction forces can provide a quantitative measure of the coordinated output of the paretic leg during hemiparetic walking. Specifically, we found that the percentage of propulsive forces generated by the paretic leg (propulsion<sub>paretic</sub> [ $P_p$ ]) can quantify the contribution of the paretic leg to the coordinated task of forward propulsion during walking. In our present study, we hypothesized that the  $P_p$  would correlate with asymmetry observed in step lengths because the generation of a step requires forces exerted by the legs to propel the body's COM. Further, we suggest that correlating the asymmetry observed in step lengths with propulsive ground reaction forces during walking can help in explaining the relationship between spatial asymmetry and walking performance after a stroke.

Therefore, the primary purpose of our study was to explore the correlation between step length asymmetry and propulsive forces in an attempt to quantify the relationship between step length asymmetry and poststroke hemiparetic walking performance. Further, we investigated how asymmetrical step lengths may be related to hemiparetic severity (as rated by Brunnstrom staging), walking speed, vertical ground reaction forces, and other spatiotemporal walking parameters (walking speed, swing time, preswing time, ability to change speed) to gain a holistic explanation of the relationship between asymmetrical step lengths and hemiparetic walking performance.

## METHODS

### Participants

We recruited 49 subjects with chronic hemiparesis (42 men, 7 women; age  $\pm$  standard deviation,  $62.7 \pm 10.2$ y; time since stroke,  $4.25 \pm 3.67$ y; affected side: left, 25; right, 24) at the Palo Alto Department of Veterans Affairs Medical Center. The data presented in this study were collected as part of a larger study that investigated the links between gait characteristics and bone density in chronic stroke survivors.<sup>11</sup> Inclusion criteria were: at least 6 months poststroke, unilateral weakness, and the ability to walk 10m in 50 seconds or less without manual assistance. Subjects were allowed to use their assistive devices (ankle-foot orthosis [AFO] and/or cane) during the testing. Subjects were excluded from the study if they had any orthopedic or neurologic conditions in addition to the stroke, had more than 1 cerebrovascular accident, or were unable to provide informed consent. Brunnstrom motor recovery stages were used to determine the severity of hemiparesis for the subjects.<sup>12</sup> Subjects varied in their ability to perform voluntary movements within and outside of flexor and extensor synergy patterns (as assessed clinically by Brunnstrom staging). Based on their Brunnstrom stage, 3 groups of subjects with differing hemiparetic severity were identified. Subjects ( $n=19$ ) in the severe hemiparesis group (Brunnstrom stage 3) were limited to movements within the synergy patterns (eg, only basic limb flexion or extension synergies can be performed voluntarily). Subjects ( $n=20$ ) in the moderate hemiparesis group (Brunnstrom stages 4–5) were able to produce some movement combinations outside of the synergy patterns. Subjects ( $n=10$ ) in the mild hemiparesis group (Brunnstrom stage 6) were able to produce both isolated

joint movements and movements in synergy patterns. All participants in the study signed a written informed consent and the Stanford Administrative Panel on Human Subjects in Medical Research approved the protocol.

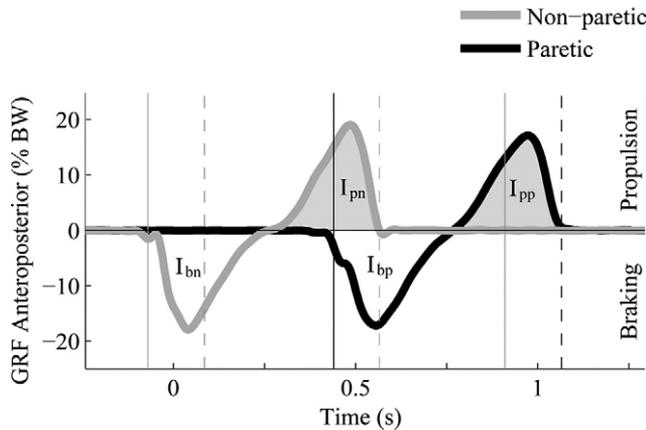
### Procedures

The subjects walked separately over the GAITRite<sup>a</sup> and force platforms<sup>b</sup> at their self-selected and fastest safe speeds to collect the spatiotemporal parameters and ground reaction forces, respectively. GAITRite is a portable instrumented electronic walkway 4.3m long and is a valid and reliable system for measuring spatiotemporal parameters.<sup>13</sup> Forceplates embedded across a 10-m walkway were used to collect 3-dimensional ground reaction forces during the gait cycle. Before testing, clear explanations were provided to the subjects regarding the importance of walking in their natural manner during the testing and avoidance of targeting the forceplates. During GAITRite data collection, the GAITRite was placed over the forceplates in the walkway, but the forceplate data were not collected while subjects were walking on the GAITRite. Subjects started walking 5 to 6 steps before the GAITRite and stopped 5 to 6 steps after passing the GAITRite to get constant speed data over the mat and avoid the effects of acceleration and deceleration. Subjects walked a total distance of 10m over the GAITRite. Three good walking trials, each at self-selected and fastest safe speeds, were collected over the GAITRite. Some subjects were asked to walk 1 or 2 more trials due to problems like tripping during walking. The number of trials collected for the forceplate data were variable and depended on whether both or at least 1 leg were determined by visual inspection to have had adequate contact on the force platforms. Ground reaction force data were acquired at 200Hz and the horizontal and vertical forces (normalized to the individual's body weight) were used for analyses. A therapist provided close supervision during the walking trials. Subjects were allowed to take rests between trials if they needed to. Walking speed was calculated by the GAITRite and no estimates of speed were used from the forceplate trials.

### Data Analyses

**GAITRite data.** We analyzed all of the collected trials (3 for each speed). The data from individual trials were averaged together to determine the spatiotemporal variables for each participant. Spatiotemporal variables included in this study were self-selected and fastest walking speed, step lengths, swing times, and preswing times (time spent in double-support phase of gait cycle). Paretic and nonparetic step length, swing time, and preswing time data were averaged only from the trials of self-selected walking speed. Subjects' self-selected walking speed was categorized as: speed less than 0.4m/s (household ambulatory); 0.4 to 0.8m/s (limited community); or speed greater than 0.8m/s (community ambulatory).<sup>14</sup> Step length asymmetry was quantified using a step length ratio (SLR), which was defined as the paretic step length (in meters) divided by the nonparetic step length (in meters). The fastest safe walking speed data were utilized to calculate the percentage change (from self-selected to fastest safe speeds) in walking speed, cadence, paretic step lengths, and nonparetic step lengths.

**Forceplate data.** We collected a minimum of 4 trials and a maximum of 15 trials to assure adequate contact on the force platforms to determine the ground reaction force patterns for each participant. The ground reaction force values that were analyzed for individual participants were variable and depended on the number of trials with good foot contacts on the



**Fig 1.** Illustration of horizontal ground reaction force impulses. Positive values (shaded area) represent propulsion. Negative values (unshaded area) represent braking. Paretic leg is the dark curve and nonparetic leg is the light curve. Abbreviations: BW, body weight; GRF, ground reaction force;  $I_{bn}$ , braking impulse by the nonparetic leg is the unshaded area under the light curve;  $I_{bp}$ , braking impulse by the paretic leg is the unshaded area under the dark curve;  $I_{pn}$ , propulsive impulse by the nonparetic leg is the shaded area under the light curve;  $I_{pp}$ , propulsive impulse by the paretic leg is the shaded area under the dark curve.

force platforms. Good foot contacts were determined if both legs made contact with the force platforms in entirety. When possible, multiple good foot contacts were averaged to generate ground reaction force values, but in 1 participant, only 1 trial could be analyzed.

Raw anteroposterior and vertical ground reaction force data were normalized to body weight and processed using a custom Matlab program.<sup>c</sup> Note that anteriorly directed forces are propulsive (positive) and posteriorly directed forces are braking (negative) (fig 1). The impulse for each leg was calculated as the time integral of the ground reaction forces (the area under the ground reaction forces curve):

$$I_{x1} = \int GRF_x dt \quad (1)$$

where I is the impulse; force component x equals v (vertical), p (propulsive), or b (braking); leg l equals p (paretic) or n (nonparetic); and GRF is the ground reaction force. Paretic propulsion ( $P_p$ ) was then calculated from the propulsive impulse:

$$P_p (\%) = I_{pp} / (I_{pp} + I_{pn}) \times 100$$

**Statistical Analyses**

A paired-sample *t* test was used to test whether the differences between the paretic and nonparetic step length were statistically significant. Relationships between the step length asymmetry (expressed as SLR), ground reaction forces, and walking speed were characterized using the Pearson correlation coefficient (*r*) and that between SLR and hemiparetic severity using the nonparametric Spearman correlation coefficient ( $\rho$ ). For other walking variables included in the study, descriptive analyses were conducted to understand their relationship with the asymmetrical patterns. All statistical analyses were performed with SPSS.<sup>d</sup>

**RESULTS**

The walking variables were collected at the self-selected walking speeds for all subjects and at the fastest safe speeds for

46 subjects. Data were not collected for 3 subjects at their fastest speeds due to safety concerns. Nineteen of the 49 subjects used a mobility aid (ie, a cane or AFO or both) to ambulate. Paired-sample *t* tests revealed that the paretic step lengths were significantly different from the nonparetic step lengths ( $P = .000$ ). Therefore, step length asymmetry was characterized and 3 patterns of step length asymmetry were identified. The symmetrical group was defined as subjects with an SLR between 0.9 and 1.1. Asymmetrical groups were those with SLR greater than 1.1 (longer paretic steps than nonparetic) and SLR less than 0.9 (longer nonparetic steps than paretic).

**Relationship Between Step Length Asymmetry (SLR) and Ground Reaction Forces**

Correlation analysis revealed a strong negative correlation between SLR and  $P_p$ , with  $P_p$  explaining 62% ( $r = -.785$ ,  $P < .001$ ) of variance in step length asymmetry (table 1). Subjects that showed impaired paretic leg propulsion ( $P_p$ ) and increased nonparetic leg propulsion walked asymmetrically with longer paretic steps than nonparetic (fig 2A). In contrast, subjects generating symmetrical ground reaction forces with the 2 legs walked nearly symmetrically (see fig 2B). Subjects generating relatively proportionate or greater  $P_p$  walked asymmetrically with longer nonparetic steps than paretic. However, the greater  $P_p$  generated by these subjects walking with longer nonparetic steps was lesser in magnitude compared to those walking symmetrically. Refer to figure 2 and compare the  $P_p$  between ground reaction force curves of the bottom and middle tracing (figs 2B, 2C).

**Asymmetrical group with longer paretic step lengths than nonparetic.** Subjects ( $n = 16$ ) who generated the least paretic propulsion ( $P_p < 20\%$ ) walked with relatively longer paretic step lengths. Five of these 21 subjects generated 5% or less  $P_p$  and walked with the longest paretic steps relative to the nonparetic leg (SLR  $> 1.5$ ) (fig 3).

**Asymmetrical group with longer nonparetic step lengths than paretic.** There were only 4 subjects who were classified as asymmetric and who walked with relatively longer nonparetic step lengths. Three of these 4 subjects generated substantial propulsive forces with the paretic leg ( $P_p > 55\%$ ); however, 1 subject generated only 25%  $P_p$ .

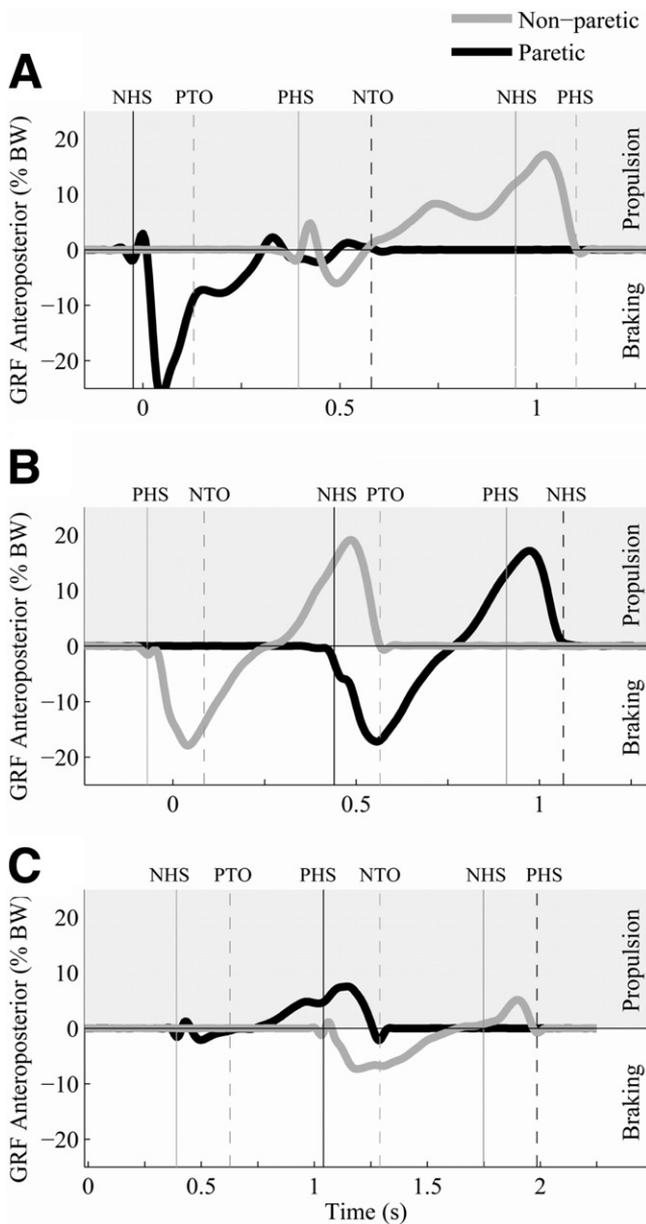
**Symmetrical group.** Twenty-four subjects walked symmetrically. Seventeen of these 24 subjects generated almost symmetrical propulsive forces ( $P_p$  range, 35%–57%) and the rest generated lesser paretic leg propulsion ( $P_p$  range, 15%–30%).

Only 10 of 49 subjects in the study population generated a net braking impulse in the preswing (normally propulsive)

**Table 1: Correlation Between SLR and Walking Variables**

Walking Variables	Step Length Asymmetry
$P_p$ (paretic leg propulsion)	-.785 <sup>†</sup>
Self-selected walking speed	-.351*
Hemiparetic severity (Brunnstrom stage)	-.526 <sup>†</sup>
Percentage weight supported during preswing phase	
Paretic preswing phase	
Weight on paretic leg	-.447 <sup>†</sup>
Weight on nonparetic leg	-.291*
Nonparetic preswing phase	
Weight on paretic leg	.072
Weight on nonparetic leg	.212

\*Significant at  $P < .05$ .  
<sup>†</sup>Significant at  $P < .001$ .



**Fig 2.** Comparison of ground reaction forces between the paretic and nonparetic legs for individual subjects walking with differing SLR. Positive values (shaded area) represent propulsion, and the positive area under the curve is the propulsive impulse. Paretic leg is the bold curve and nonparetic leg is the light curve. (A) Subject with severe hemiparesis walking with SLR equal to 1.47 (ie, SLR > 1.1) and at a speed of 0.71m/s generates decreased paretic leg propulsion ( $P_p$ ). (B) Subject with mild hemiparesis walking at SLR equal to 0.98 (ie,  $0.9 < SLR < 1.1$ ) at a speed of 0.75m/s generates symmetrical propulsive impulse. (C) Subject with mild hemiparesis walking with SLR equal to 0.68 (ie, SLR < 0.9) and at a speed of 0.52m/s generates relatively greater paretic leg propulsion,  $P_p$  (although low in magnitude). Abbreviations: NHS, nonparetic heel strike; NTO, nonparetic toe off; PHS, paretic heel strike; PTO, paretic toe off.

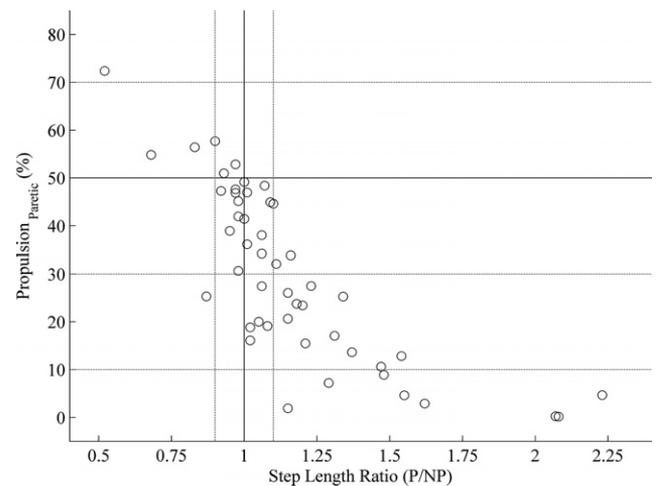
phase of the gait cycle and these 10 subjects walked at SLR greater than 1.1, with 5 of 10 subjects walking at SLR greater than 1.5. Nine of these 10 subjects used a mobility aid for ambulation and 1 subject walked independently. We analyzed

the data for subjects who used a mobility aid separately from those who did not to investigate whether the relationship between step length asymmetry and paretic leg propulsion changed by using a mobility aid. Subjects walking with a mobility aid generated less  $P_p$  in comparison to those who walked without one. However, the relationship between SLR and  $P_p$  did not differ for those who did or did not use a mobility aid.

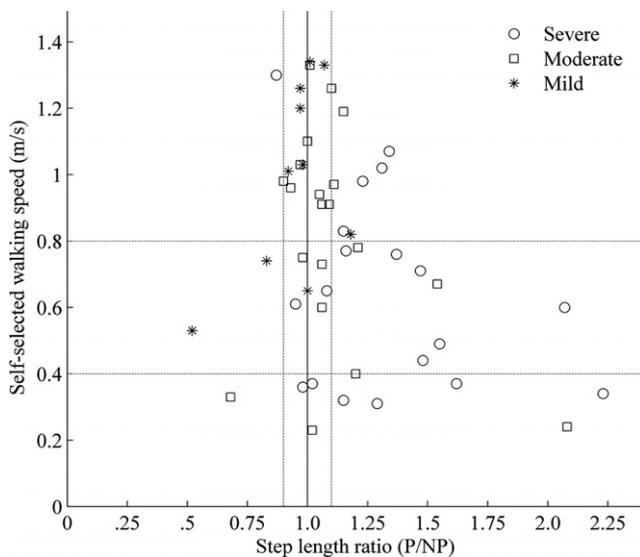
With respect to the vertical ground reaction force, all subjects (irrespective of their step length asymmetry pattern) supported a greater percentage of body weight on the nonparetic leg than the paretic leg during the 2 double-support phases in the gait cycle. However, moderate correlations ( $r = -.447$ ,  $P < .001$ ) were found only between SLR and percentage of body weight supported on the paretic leg during the preswing phase of the paretic leg (see table 1).

**Relationship Between Asymmetrical Step Lengths, Hemiparetic Severity, and Walking Speed**

While SLR correlated weakly with walking speed ( $r = -.351$ ,  $P < .05$ ), a stronger correlation existed between SLR and hemiparetic severity ( $\rho = -.526$ ,  $P < .001$ ) (see table 1). Fourteen of the 19 subjects with severe hemiparesis walked asymmetrically with relatively longer paretic steps than nonparetic and yet walked at differing walking speeds (fig 4). Note that 4 subjects with severe hemiparesis that walked asymmetrically with longer paretic steps generated much less paretic leg propulsion ( $P_p < 25\%$ ) and yet walked at speeds greater than 0.8m/s (community ambulatory) (see fig 4).<sup>14</sup> In contrast, the 3 subjects (see fig 4) with mild hemiparesis (stage 6) who walked symmetrically or asymmetrically (with longer nonparetic steps) generated much greater paretic leg propulsion ( $P_p \geq 45\%$ ) and yet walked at slower speeds between 0.4 and 0.8m/s (limited community ambulatory).<sup>14</sup>



**Fig 3.** Relationship between step length ratio and propulsion<sub>paretic</sub>. The solid vertical line indicates symmetric steps (SLR=1), vertical dashed lines indicate the SLR subdivisions at SLR equal to 0.9 and SLR=1.1. Solid horizontal line indicates symmetric propulsive force generation by the paretic leg ( $P_p=50\%$ ), horizontal dashed lines indicate differing levels of paretic leg propulsion (10%, 30%, and 70%  $P_p$ ). Step length ratio quantifies step length asymmetry and propulsion<sub>paretic</sub> quantifies the contribution of the paretic leg to the task of propulsion. Note the decreasing paretic propulsion as SLR increases. Abbreviations: Propulsion<sub>paretic</sub>, paretic leg propulsion (in percent); NP, nonparetic leg; P, paretic leg.



**Fig 4. Relationship between step length asymmetry, walking speed, and hemiparetic severity.** The solid vertical line indicates symmetric steps (SLR=1), vertical dashed lines indicate the SLR subdivisions at SLR equal to 0.9 and SLR equal to 1.1. Horizontal dashed lines indicate subdivisions of walking speeds (<0.4m/s, household walkers; 0.4–0.8m/s, limited community walkers; >0.8m/s, community walkers). Note that subjects with different SLR walk at all levels of walking speeds, yet the majority of those with severe hemiparesis walk asymmetrically at SLR greater than 1.1. Also, the 4 subjects with severe hemiparesis walked at speeds greater than 0.8m/s. These subjects walked asymmetrically with SLR greater than 1.1 and generated  $P_p$  less than 25%. Contrast the 3 subjects with mild hemiparesis that walked at speeds between 0.4 and 0.8m/s. One of these walked symmetrically ( $0.9 < SLR < 1.1$ ) and 2 others walked asymmetrically ( $SLR < 0.9$ ) and generated  $P_p$  of 45% or greater. Abbreviations: NP, nonparetic leg; P, paretic leg.

**Relationship Between Step Length Asymmetry, Time Spent in Preswing, and Swing Time**

Only 8 of 49 subjects spent greater than 20% of cycle time during the paretic preswing phase (vs 10%–20% cycle time in their nonparetic preswing). These 8 subjects walked asymmetrically with longer paretic steps than nonparetic. With respect to swing time, only 2 of 49 subjects spent greater time swinging their paretic than the nonparetic leg. Subjects walking at SLR greater than 1.1, on an average, spent the greatest time swinging their paretic leg.

**Relationship Between SLR, Change in Gait Speed, and Parameters That Contribute to Change in Speed**

Absolute mean differences were evaluated for these analyses. Subjects (n=46) walking symmetrically increased paretic and nonparetic step lengths and cadence at faster walking speeds. In contrast, those walking asymmetrically at SLR greater than 1.1 had little increase in their paretic step length at the faster walking speeds even though they increased their cadence as much as the symmetrical group (fig 5).

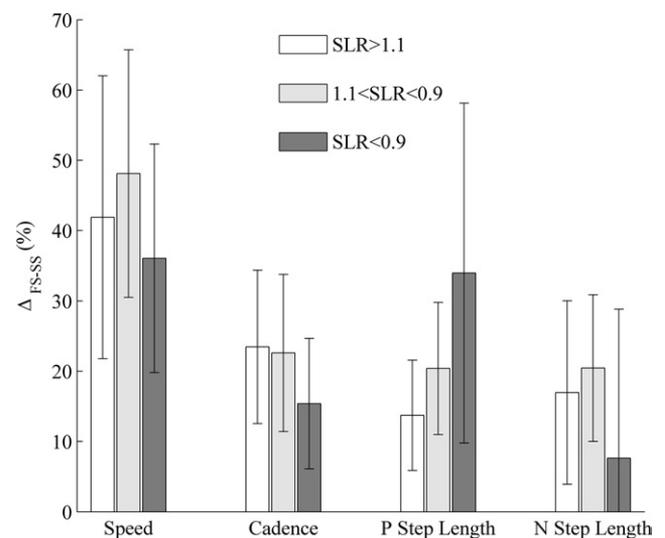
**DISCUSSION**

**Relationship Between Step Length Asymmetry and Propulsive Forces During Hemiparetic Walking**

Step length asymmetry during walking is related to propulsive forces generated by persons walking with hemiparesis. Our data revealed that subjects generating relatively lesser

propulsive forces with the paretic leg walked asymmetrically with longer paretic steps than nonparetic ( $SLR > 1.1$ ) On the other hand, subjects walking symmetrically ( $0.9 < SLR < 1.1$ ) generated near symmetrical propulsive forces with the 2 legs. In figure 2, comparison of  $P_p$  between subjects with an SLR greater than 1.1, with an SLR between 0.9 and 1.1, and with an SLR less than 0.9 indicates that there may be distinct differences in paretic leg propulsion between subjects with different patterns of step length asymmetry.

To our knowledge, there is little direct evidence for the mechanisms that control step length in normal and hemiparetic walking. However, indirect evidence for the control of step length during walking is provided by a few studies. Varraine et al<sup>15</sup> suggest 2 potential controlling mechanisms for intentionally lengthening a stride in healthy subjects: control of trunk progression and control of leg trajectory. In their study, subjects were able to lengthen their stride by generating greater propulsive forces. The increased propulsive forces enabled the trunk to progress further forward and thereby generate a longer step. Additionally, subjects took a longer step by holding the leg longer in the swing phase. Further, recent studies have highlighted the causal relationships between muscle activity in preswing and the resulting swing leg trajectory.<sup>16-18</sup> These studies indicate that kinematics of the leg in its preswing phase affect trajectory of the leg in its swing phase and thereby, magnitude of the step length. This implies that the leg producing greater forward propulsion in preswing might take the longer step length. However, the results from our study suggest the opposite. We showed that persons generating impaired paretic leg propulsion walked with a relatively longer paretic step. These persons generating impaired paretic leg propulsion also generated relatively greater nonparetic propulsion, likely to compensate for the lesser paretic leg propulsion. For example, in figure 2, compare the relative contributions of nonparetic propulsion in the top and middle ground reaction force tracings. These results suggest that a high SLR (ie, paretic step length greater than nonparetic step length) is in large part the result of the relatively greater nonparetic leg propulsion. For



**Fig 5. Change in speed, cadence, and individual step lengths in subjects walking at different SLR (SLR > 1.1 [n=21]; 0.9 < SLR < 1.1 [n=21]; SLR < 0.9 [n=4]).** Subjects walking with SLR greater than 1.1 increase their speed by primarily increasing their cadence, with little increase in the paretic step length. Abbreviation:  $\Delta_{FS-SS}$ , change in speed from self-selected to fastest safe speed.

instance, greater forward propulsion by the nonparetic leg in its stance phase will cause the trunk, including the pelvis, to move forward. This forward motion of the pelvis will increase with increased propulsion and can cause the swinging paretic leg to move forward relative to the ground even if it moves little relative to the pelvis. Therefore, greater nonparetic leg propulsion is one mechanism for the longer paretic steps (high SLR). Further, persons with high SLR also spent a longer time swinging their paretic leg than others who walked with symmetrical steps. Therefore, one might hypothesize either both greater nonparetic leg propulsion or a longer paretic swing phase as potential candidates to explain the mechanisms underlying a relatively longer paretic step length.

The strong relationship between the patterns of step length asymmetry and propulsive force asymmetry might suggest a mechanical relation between step length and propulsive force. For example, if the leg were to be considered an inverted pendulum, the generation of horizontal forces would be directly related to the position of the foot relative to the body's COM. Specifically, foot placement anterior to the COM (as during heel strike) would induce a braking force and foot placement posterior to the COM (as in preswing phase) would induce a propulsive force. In this sense, an asymmetry in the placement of the feet may induce asymmetrical propulsive forces when the foot is placed more anterior to the COM than posterior. However, the inability to place the foot further behind the COM than forward (as with longer paretic steps than nonparetic) suggests specific impairments underlying the asymmetrical step lengths. For example, the inability to achieve adequate hip extension may limit the propulsive forces exerted during the terminal stance. Furthermore, during the terminal stance of the paretic stride the paretic foot is likely posterior to the body's COM, and yet there is no propulsive force generated (see fig 2A). Therefore, it is more likely that there may be an active reduction in propulsive force generation. The active reduction in propulsive force generated in the preswing may, in turn, suggest impaired uniaxial ankle plantarflexor activity.<sup>19</sup> On the contrary, in the participants walking with relatively shorter paretic steps (SLR < 0.9), the greater paretic propulsive force generation suggests that plantarflexors may be providing reasonable propulsion. Stepping, however, depends not only on the ability of the plantarflexors to propel the body forward but also on the ability of the hip flexors to generate power to the swinging leg.<sup>20</sup> Therefore, having shorter paretic steps relative to nonparetic steps may indicate an inability to advance the paretic leg due to impaired swing initiation by the hip flexors. In addition to direct mechanical effects of foot placement on propulsive force generation, it is likely that the mechanisms underlying asymmetrical steps reflect distinct muscular impairments that determine the observed patterns of step length asymmetry during hemiparetic walking. Future studies targeted at investigating the underlying muscular impairments may further determine the underlying causes for high SLR. Yet, the strong relationship between SLR and propulsion can be utilized in the clinic as a tool to distinguish persons in their ability to generate propulsive forces. Beyond simply promoting symmetry, SLR can be utilized to develop individual goals that train propulsive force production, equalize bilateral biomechanical involvement by improving hip extension, or promote paretic step initiation.

#### **Relationship Between Step Length Asymmetry, Walking Speed, and Hemiparetic Severity**

We were also able to investigate the relationship between walking speed, hemiparetic severity, and asymmetry in step lengths. A weak relationship between step length asymmetry

and walking speed was observed, indicating that asymmetrical patterns need not necessarily limit the attained walking speed. However, hemiparetic severity (as rated by Brunstrom staging) seemed to predict step length asymmetry because the majority of subjects with severe hemiparesis walked asymmetrically at SLR greater than 1.1. Furthermore, differences in  $P_p$  between the persons with mild and severe hemiparesis were unrelated to the attained walking speed. For example, in figure 4, 4 subjects with severe hemiparesis had impaired  $P_p$  and yet they were walking at speeds greater than 0.8m/s. In contrast, 3 subjects with mild hemiparesis generated greater  $P_p$  and yet walked at slower speeds between 0.4 and 0.8m/s. The weak relation between  $P_p$  and walking speed indicates that other compensatory mechanisms could help some persons to attain a relatively functional walking speed. Quantification of these compensatory mechanisms may be difficult when speed alone is the outcome measure because walking speed is the net outcome of the 2 legs. However, asymmetrical step lengths might indicate compensation in those persons walking with a high SLR and faster walking speeds compared with those walking with a high SLR and slower walking speeds. This is because subjects with relatively longer paretic steps would have lesser paretic leg propulsion, and if they continue to walk at faster speeds they might accomplish these speeds via compensatory strategies. For example, one of the ways to attain a faster speed (ie, acceleration of the body's COM) would be to generate greater propulsive forces with the nonparetic leg that serves to accelerate the COM forward. Other compensations can also arise from the paretic leg itself or from the trunk (eg, forward lean) to attain relatively functional walking speeds despite decreased propulsive force with the paretic leg.

#### **Relationship Between Step Length Asymmetry, Paretic Preswing Time, and Vertical Ground Reaction Forces**

Furthermore, we were able to determine the relationship between step length asymmetry, other spatiotemporal parameters and vertical ground reaction forces. The evidence that impaired paretic leg function prolongs the paretic preswing phase supports our finding that persons walking at SLR greater than 1.1 supported less weight on the paretic leg during the preswing phase. This finding thereby increases the need to develop compensatory strategies to overcome these deficits.<sup>8</sup> In particular, note that in our study we allowed participants to walk naturally as they would in the community and 19 persons used some mobility aid for ambulation even during the testing. Although persons walking with a mobility aid generated less  $P_p$  in comparison to those who walked without one, the relationship between SLR and  $P_p$  did not change while analyzing only the data for those subjects who used an aid or those who did not. This corroborated our hypothesis that a high SLR was related to specific problems in propelling the body forward with the paretic leg. However, the high SLR may neither necessarily limit the attained speed nor substantially limit persons from changing their walking speeds. As revealed in figure 5, compared with the symmetrical group, persons with high SLR seemed to primarily increase their speed by increasing cadence with much less increase in the paretic step lengths. This indicates that persons walking with asymmetrical step lengths may use different strategies to increase their walking speeds. Further, even though the subjects with SLR greater than 1.1 walked with relatively longer paretic steps than nonparetic at their self-selected walking speeds, they were unable to change the paretic step length as much as the nonparetic when changing their speed.

## CONCLUSIONS

We were able to provide some insights into the relationship between asymmetrical step lengths and hemiparetic walking performance. Asymmetry in step lengths strongly relates to the propulsive forces generated by the paretic leg. Greater nonparetic leg propulsion to offset the impaired paretic propulsion is likely one of the mechanisms for the high SLR (paretic step length greater than nonparetic step length). Despite mechanical relations between foot placement and force generation that are expected, we believe that there are additional muscular impairments underlying the asymmetrical patterns. However, further research is warranted to confirm this. Yet, the strong relationship between SLR and propulsion can be used in the clinic as a measure to evaluate the propulsive forces generated by the paretic leg. We were also able to provide a basis to evaluate the different asymmetrical patterns by correlating the asymmetry observed in step lengths with propulsive ground reaction forces during hemiparetic walking. Moreover, the relationship between SLR, speed, and hemiparetic severity indicates that SLR, when used along with speed as an outcome measure, can help understand compensatory strategies that some persons (who are asymmetrical and yet walk at faster speeds) use to offset the lesser propulsive force ability of the paretic leg. The relationship between SLR and other spatiotemporal walking parameters further reveals how asymmetrical step lengths may affect hemiparetic walking. In summary, we propose that SLR is a promising tool that rehabilitation therapists might use to further the understanding of hemiparetic walking performance. Clinically, this would assist in the identification of walking impairments in hemiparetic persons and in tailoring locomotor retraining specifically to address the root causes of impaired ambulation for each person.

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## Suppliers

- a. CIR Systems Inc, 60 Garlor Dr, Havertown, PA 19083.
- b. Advanced Medical Technology Inc, 176 Waltham St, Watertown, MA 02472.
- c. The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.
- d. Version 12.0; SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.