Control of Lead and Trail Limbs During Obstacle Crossing Following Stroke

Background and Purpose. Obstacle crossing is compromised following stroke. The purpose of this study was to quantify modifications during obstacle clearance following stroke. Subjects. Twelve subjects with stroke and 12 subjects without stroke participated in the study. Methods. Kinematic variables were measured while participants crossed a 4-cm-high obstacle. Subjects with stroke walked at a self-selected speed; subjects without stroke walked at a comparable speed and at a self-selected speed. Results. Several modifications were observed following stroke with both groups walking at self-selected speeds. The affected lead limb was positioned closer to the obstacle before crossing. Affected trail-limb clearance over the obstacle was reduced. Both affected and unaffected lead and trail limbs landed closer to the obstacle after clearance. Swing time was increased in the affected lead limb after obstacle clearance. Fewer modifications were detected at matched walking speed; the trail limb still landed closer to the obstacle. Discussion and Conclusion. Modifications during obstacle crossing following stroke may be partly related to walking speed. The findings raise issues of safety because people with stroke demonstrated reduced clearance of a 4-cm obstacle and limb placement closer to the obstacle after clearance. [Said CM, Goldie PA, Culham E, et al. Control of lead and trail limbs during obstacle crossing following stroke. Phys Ther. 2005;85:413–427.]

Key Words: Biomechanics, Cerebrovascular accident, Gait disorders: neurologic.

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Independent walking in the home and community requires gait pattern modifications to negotiate environmental features, such as obstacles. A previous study demonstrated that obstacle crossing was compromised following stroke, even after walking without physical assistance was regained. That study was limited because it examined only the lead-limb crossing step. Because difficulty in stepping over small obstacles may contribute to the high falls rate following stroke, a more detailed understanding of the underlying movement disorders is crucial. This article examines the control of affected and unaffected lead- and trail-limb trajectories during obstacle crossing following stroke.

Obstacle crossing has 3 phases: approach to the obstacle, obstacle crossing, and landing after the obstacle. Lead- and trail-limb trajectories during each of these phases can be measured using spatial and temporal variables. Limb placement before the obstacle provides insight into modifications during the approach phase. Lead- and trail-limb obstacle clearance are examined during the crossing phase because inadequate clearance may lead to a trip and subsequent fall. Placement of the limb after the obstacle also is crucial because poor limb placement may increase the risk of contact with the obstacle. Temporal variables provide information about the time required to modify limb trajectories. Pre-obstacle swing time, from toe-off to obstacle clearance, provides insight into the time required to prepare the limb for clearance. Post-obstacle swing time, from obstacle clearance to foot contact, provides information about the time required to prepare the limb for landing. Consideration of spatial and temporal variables from each of these phases is required to fully describe obstacle clearance.

Analysis of lower-limb joint angles provides further insight into this complex task. For example, lead-limb clearance over an obstacle in subjects without stroke is achieved by a combination of swing-limb flexion and "hip hiking" on the stance limb. Swing-limb hip flexion and abduction, knee flexion, and ankle dorsiflexion describe the swing limb’s contribution to lead-limb clearance. The contribution of the stance (trail) limb to clearance can be evaluated by examining pelvic obliquity and stance hip height, which can be further explored by examining stance-limb hip, knee, and ankle angles. Examination of kinematic variables before, during, and after obstacle crossing in both the stance and swing limbs, therefore, provides information about the control of lead- and trail-limb trajectory following stroke.

Because stroke is frequently a unilateral disorder, we predicted that the limb with which subjects first stepped over the obstacle would influence limb trajectory during obstacle crossing. The current study aimed to maximize chances that subjects with stroke would lead with both the affected and unaffected limbs (in different trials).
This allowed the movement patterns of the affected and unaffected limbs to be compared with performance of people without stroke. Reduced gait speed following stroke also may influence limb control during obstacle crossing. The relationship between the spatial and temporal characteristics of obstacle crossing and walking speed during obstacle crossing has not been explored. Given the established relationship between spatial and temporal variables and gait speed,13,14 we expected that reduced speed would alter limb placement before and after the obstacle (Fig. 1). To determine the impact of slower gait speed on obstacle crossing, subjects with stroke were compared with subjects without stroke walking at both a self-selected speed and at a speed matched to that of the subjects with stroke. We predicted that fewer differences in the movement patterns would be detected when walking speed was matched between groups.

The purpose of this experiment was to determine whether control of lead- and trail-limb obstacle crossing was abnormal following stroke. We compared movement patterns on the affected and unaffected limbs of subjects with stroke with those of subjects without stroke walking at self-selected and matched speeds.

**Method**

**Subjects**

Twelve subjects with stroke and 12 subjects without stroke were matched for age, sex, and height. Subjects with a recent (less than 12 months) cortical or subcortical stroke who were receiving inpatient or outpatient rehabilitation for gait or balance disorders and were able to follow simple verbal instructions were eligible to participate. Participants had to be able to walk without a walking aid, orthosis, or assistance for a minimum of 10 m multiple times with rests. Volunteers were excluded if they had other medical disorders that may have affected ambulation, a history of uncorrected visual disturbances, a brain-stem or cerebellar infarct, or a previous stroke that required hospitalization for more than 72 hours. For the subjects with stroke, the mean age was 65.1 years (SD=16.6), the mean height was 169.5 cm (SD=9.4), and the mean leg length was 86.6 cm (SD=6.6). Subjects were tested a median of 62 days poststroke. Data for individual subjects are provided in Table 1. Results from our previous study3 indicated that 38% of subjects with stroke admitted for rehabilitation met the criteria.

Subjects without stroke were recruited from personal contacts, senior citizens clubs, and relatives of subjects with stroke. The participants were required to be community ambulators and were excluded if they had any history of stroke or other medical disorders that affected ambulation, uncorrected visual disturbances, or more than one fall in the preceding 12 months. This information was obtained via a telephone interview, and subjects over the age of 65 years were screened by a neurologist (AH/JO). For the subjects without stroke, the mean age was 64.3 years (SD=16.7), mean height was 172.2 cm (SD=9.5), and mean leg length was 88.6 cm (SD=5.7). Independent t tests did not detect significant differences between the 2 groups for age, height, or leg length.

**Apparatus**

A 6-camera Vicon 512 3-dimensional motion analysis system* and a Kistler forceplate (Performance System 9281B†), positioned in the middle of the walkway, were used to obtain kinematic and kinetic data. Only kinematic data will be reported. The mean error using the Vicon system has been estimated to be less than 1 mm.15

Two red balsa wood obstacles measuring 4 cm × 1.5 mm thick × 60 cm long were used for data collection. One obstacle was positioned after the forceplate, approximately 5 m from the start of the walkway. A “4-cm-high” obstacle was created by securing the obstacle vertically to the floor with a small amount of adhesive gum; a “4-cm-wide” obstacle was created by placing the obstacle flat on the ground perpendicular to the path of progres-

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† Kistler Instrumente AG, Eulachstrasse 22, Postfach, CH-8408 Winterthur, Switzerland.
The second obstacle was used for demonstration. Subjects wore a lightweight safety belt around the waist and were accompanied by a physical therapist. Twenty-one 2.5-cm reflective markers identified various landmarks on the subject and the obstacle. The 2 thigh and 2 tibia markers were on short “wands” to enhance visibility. A triangular device with 3 markers positioned on it and a known endpoint was used to identify the sole of the shoe. Two knee alignment devices (KADs) were required during the static trials to identify the flexion-extension axis of the knee. BodyBuilder Version 3.5* and Vicon Clinical Manager Version 1.37 (VCM)* software packages were used to process the data. Additional equipment required for clinical tests to provide descriptive data about subjects included a stopwatch, a 14-m walkway, a flight of 4 steps, and a small beanbag.16–18

Procedure

Informed consent was obtained from all subjects. To provide descriptive information about the subjects with stroke, data such as the lesion site, Functional Independence Measure (FIM) score,18 unobstructed gait speed, score on the walk section of the Motor Assessment Scale (MAS),16 and sensory loss or neglect were collected by the primary investigator (CMS).19 The presence of spatial neglect, perceptual disorders, or cognitive deficits were obtained from neuropsychology reports, in conjunction with written notes from treating therapists. Results are presented in Table 1.

An orthoptist examined all subjects for visual acuity, field defects, diplopia, and any other visual deficits. Two subjects with stroke (subjects 7 and 10) had reduced acuity in one eye, but were included because all subjects had corrected binocular visual acuity greater than 20/40).

Subjects wore loose-fitting shorts, their own walking shoes, and any prescription eyewear usually worn during ambulation. Anthropometric measurements were obtained as outlined in the VCM manual to calculate hip, knee, and ankle joint locations.20,21 Reflective markers were attached using double-sided adhesive tape. Lower-limb markers were placed as described in the VCM manual. Additional markers were placed on the fifth proximal phalanx on the right and left feet to allow the most distal point of the toe of the shoe to be identified. Markers also were placed on the right and left acromions to identify the position of the trunk. Two markers were placed on either end of the obstacle.

A static trial was performed prior to data collection to provide a reference point for markers. Briefly, 2 to 3 seconds of data were collected with subjects standing in a stationary position. For this trial, only the knee markers

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**Table 1.**

Characteristics of Subjects With Strokea

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Age (y)</th>
<th>Lesion Site</th>
<th>Days Poststroke</th>
<th>Sensory Lossb</th>
<th>Visual Field Deficit</th>
<th>FIM Total Score</th>
<th>MAS Walk Section Score</th>
<th>Gait Aid</th>
<th>Gait Speed (m/min)</th>
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<tr>
<td>1c</td>
<td>74</td>
<td>Left internal capsule infarct</td>
<td>15</td>
<td>Nil</td>
<td>Nil</td>
<td>114*</td>
<td>4*</td>
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<td>Nil</td>
</tr>
<tr>
<td>2c</td>
<td>43</td>
<td>Right occipital lobe, frontoparietal cortical infarct</td>
<td>167</td>
<td>Nil</td>
<td>Nil</td>
<td>116 3</td>
<td>SPS 31.3</td>
<td></td>
<td></td>
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<tr>
<td>3d</td>
<td>76</td>
<td>No lesion on CT, clinically right lacunae infarct</td>
<td>75</td>
<td>Nil</td>
<td>Nil</td>
<td>115</td>
<td>3</td>
<td>Frame f 21.4</td>
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<tr>
<td>4c</td>
<td>74</td>
<td>Right posterior cerebral artery infarct</td>
<td>137</td>
<td>Left</td>
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<td>123</td>
<td>6</td>
<td>Nil</td>
<td>77.9</td>
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<td>42</td>
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<td>67</td>
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<td>Nil</td>
<td>122</td>
<td>6</td>
<td>Nil</td>
<td>74.1</td>
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<td>6</td>
<td>60</td>
<td>Left frontal hemorrhage</td>
<td>360</td>
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<td>Nil</td>
<td>122</td>
<td>6</td>
<td>Nil</td>
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<td>4</td>
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<td>62</td>
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<td>Left</td>
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<td>Nil</td>
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<td>Left putamen hemorrhage</td>
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<td>10</td>
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<td>Right external capsule stroke</td>
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<td>4</td>
<td>Nil</td>
<td>48</td>
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<tr>
<td>11</td>
<td>79</td>
<td>Left occipital infarctg</td>
<td>39</td>
<td>Right</td>
<td>Right hemianopia</td>
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<td>5</td>
<td>Nil</td>
<td>52.2</td>
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<tr>
<td>12</td>
<td>41</td>
<td>Right watershed infarct</td>
<td>51</td>
<td>Nil</td>
<td>Nil</td>
<td>126</td>
<td>6</td>
<td>83</td>
<td></td>
</tr>
</tbody>
</table>

*a* FIM = Functional Independence Measure, MAS = Motor Assessment Scale, CT = computed tomography.

*b* Sensation was tested by asking the subjects to identify where the examiner had touched them with a cottonwool ball.

+c Medical circumstances resulted in incomplete clinical data for subjects 1 and 2. Asterisked results were obtained from the medical history.

*d* Did not complete testing due to fatigue. No data available for unaffected lead limb over wide obstacles.

*e* Did not lead with the unaffected limb in any trials.

*f* Subject 4 also walked with a single-point stick (SPS) and supervision.

*g* An old lesion was detected on CT. No clinical signs.
were replaced with the KADs. A second static trial identified the edges of the shoes. A triangular device with a known endpoint was used to identify the most distal point of the toe, the edge of the heel, and the widest medial and lateral points of the shoe. BodyBuilder software used this information to create a virtual marker at each point, identifying the edges of the shoe.

Subjects performed 4 unobstructed trials walking at a comfortable speed to familiarize themselves with the experimental setting. They then performed 8 trials on each of 2 obstacle conditions: 4 cm high and 4 cm wide. This procedure provided sufficient trials on each condition to maximize the chances of subjects leading with both limbs, while limiting fatigue. Order of obstacle presentation was counterbalanced and randomly allocated. Following a minimum 10-minute rest, subjects without stroke repeated the test at a speed matched to that of the person with stroke to whom they were matched. The unobstructed trials provided practice. Other than being asked to walk slower, subjects without stroke were provided no additional instructions regarding obstacle crossing. Subjects with stroke performed a maximum number of 20 trials. Subjects without stroke performed a total of 40 trials: 20 at a self-selected speed and 20 at the speed of the person with stroke.

Subjects were instructed to walk at a comfortable speed and step over the obstacle without contacting it or overbalancing. Prior to the trials, subjects inspected the demonstration obstacle visually and manually. The therapist demonstrated one walk with the obstacle in place. Subjects were reminded to perform the task within their limits of safety and to stop if they felt at risk. A therapist walked to the side and slightly behind the subject and held the safety belt lightly to provide assistance, if required. Subjects received a minimum of 1 minute of rest between trials and a minimum of 10 minutes of rest after the unobstructed gait trials and after the first series of obstructed trials. To maximize chances of obtaining data for both the affected and unaffected lead limbs, subjects were instructed to alternate the limb with which they commenced walking.

**Data Processing**

Data were reconstructed and labeled in the Vicon 512 workstation. The first trial in each condition with adequate data (minimal marker loss during the strides of interest and a clean forceplate strike, if available) was selected for further processing.

Data were filtered using a 3-point weighted average procedure provided by the BodyBuilder software. Virtual markers were created at the most distal point of the toe and heel and at the most medial and lateral points of the foot, using the data obtained from the static trial. The VCM software was used to obtain lower-limb kinematic data. Hip joint centers were calculated using the model developed by Davis et al.20 Data from both BodyBuilder and VCM software were exported to Microsoft Excel2 for data reduction.

**Dependent Variables**

Measurements of lead- and trail-limb pre-obstacle distance, toe clearance, and post-obstacle distance were obtained as illustrated in Figure 1. Measurements of foot contact and toe-off were obtained, using BodyBuilder software, by visually inspecting the position of the virtual markers on the heel and the toe. Pre-obstacle swing time (from toe-off to toe clearance) and post-obstacle swing time (from toe clearance to foot contact) were calculated for the lead and trail limbs. BodyBuilder software was used to calculate horizontal foot-contact velocity and the angle of the foot with respect to the floor at foot contact.

Measurements of hip flexion, hip abduction, knee flexion, and ankle dorsiflexion on the lead and trail limbs were obtained using VCM software. Measurements of pelvic obliquity, pelvic rotation, and pelvic tilt also were obtained. Average crossing gait speed was calculated by averaging the speed for the lead and trail crossing strides. The height of the stance-limb hip joint was measured as an indication of the stance-limb contribution to swing-limb elevation.

**Data Analysis**

The majority of data did not differ significantly from a normal distribution ($P > .05$), as determined by the Shapiro-Wilks test$^{22}$; therefore, parametric analysis was used. Independent $t$ tests were used to determine whether gait speed differed between subjects with stroke and subjects without stroke. Because groups were matched for age, sex, and height, they were treated as related samples for all other comparisons.$^{23}$

The primary purpose of the study was to document differences between the movement patterns used by subjects with stroke and subjects without stroke, so a limited number of planned comparisons were performed.$^{24}$ Subjects without stroke were assigned an “affected” limb and an “unaffected” limb, in accordance with the matched subject with stroke. Comparisons between groups at self-selected speed then were made separately for the affected and unaffected limbs. Based on the previous study,$^{2}$ directional hypotheses for lead-limb post-obstacle distance, lead-limb toe clearance, and trail-limb pre-obstacle distance between groups were analyzed using one-tailed matched-pairs $t$ tests. No data supported directional hypotheses for lead-limb pre-
obstacle distance, trail-limb clearance, trail-limb post-obstacle distance, or lead- or trail-limb pre-obstacle or post-obstacle swing time. Two-tailed matched-pairs t tests were used for these variables. Data obtained for the affected and unaffected limbs of the subjects with stroke were then compared with data from subjects without stroke at matched speed using 2-tailed matched-pairs t tests for all comparisons.

Interpretation of results required an approach that balanced the risk of type I and type II errors. To reduce the risk of type I error, a Bonferroni correction was used to correct for the 4 comparisons for each variable, resulting in a significance level of .0125. This increased the risk of type II error, which is of concern, given the novelty of this research area. To reduce risk of type II errors, results between the corrected and uncorrected significance levels were interpreted as “suggestive of significance, but not definitive,”25(p7) thereby identifying areas that may require future investigation.24

Lower-limb kinematic data were examined visually to provide insight into the way in which movements were performed. Due to the small numbers of subjects and the large number of potential comparisons, these data were not analyzed statistically.

To determine whether the contribution of the stance limb to clearance differed between the groups, the height of the stance-limb hip joint was compared between groups using a repeated-measures analysis of covariance.26 Because we expected that hip joint height varied with leg length, the difference in leg length between groups was used as a covariate.

**Results**

Subjects with stroke either contacted the obstacle or lost balance on 8 out of a total of 186 obstructed trials. All contacts occurred during lead-limb landing. Results will be presented from performance on the “high” obstacle because there was no difference in performance on the “high” obstacle compared with performance on the “wide” obstacle. One subject with stroke always led with the affected limb. Kinematic data for one subject with stroke was only available when leading with the unaffected limb over the high obstacle.

As predicted, self-selected gait speed was reduced following stroke (Tab. 2) compared with subjects without stroke ($P<.01$). No differences in gait speed were detected between groups when subjects without stroke walked at a speed matched to that of the subjects with stroke ($P>.05$).

### Table 2.

Mean and Standard Deviation for Gait Speed (in Meters per Second) for Each Condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Subjects With Stroke</th>
<th>Subjects Without Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{X}$</td>
<td>SD</td>
</tr>
<tr>
<td>Affected lead limb</td>
<td>0.76</td>
<td>0.29</td>
</tr>
<tr>
<td>Unaffected lead limb</td>
<td>0.83</td>
<td>0.29</td>
</tr>
</tbody>
</table>

* Significantly different ($P<.01$) from subjects with stroke.

**Modifications to the Gait Pattern Before the Obstacle**

As illustrated in Figure 2, pre-obstacle distance of the affected lead limb was reduced in the subjects with stroke when groups were compared at a self-selected speed ($t_{(11)}=3.38$, $P=.006$). When leading with the unaffected limb, the difference was suggestive of significance ($t_{(10)}=2.94$, $P=.015$), which persisted when examined between groups walking at matched speed ($t_{(10)}=2.50$, $P=.031$). In contrast, trail-limb pre-obstacle distance did not differ between groups at either gait speed ($P>.05$).

**Lead-Limb Obstacle Clearance**

Figure 3 demonstrates that subjects with stroke did not modify lead-limb toe clearance as they cleared the high obstacle, compared with subjects without stroke at either speed ($P>.05$). Visual inspection of the lead-limb hip, knee, and ankle motion at lead-limb clearance suggested that movement patterns utilized following stroke were similar to patterns used by subjects without stroke. Two deviations were noted (Fig. 3). Subjects with stroke appeared to have an increased anterior pelvic tilt, particularly compared with subjects without stroke walking at matched gait speed. Subjects with stroke also appeared to have an increased amount of hip abduction motion.

Inspection of kinematic data for the stance (trail) limb (Fig. 3) suggests that subjects with stroke were in a more flexed position during lead-limb clearance. More flexion was observed in the hip, knee, and ankle joints of the affected and unaffected stance limbs compared with subjects without stroke walking at a similar speed. The height of the hip joint of the affected or unaffected stance limb at lead hip, knee, and ankle joint limb clearance did not differ between groups at either speed ($P>.05$).

**Lead-Limb Contact After the Obstacle**

Figure 4 illustrates that lead-limb post-obstacle distance was reduced for both limbs following stroke compared with subjects without stroke walking at self-selected speed (affected limb: $t_{(11)}=3.79$, $P=.003$; unaffected limb: $t_{(10)}=6.89$, $P=.000$). Unaffected lead-limb post-
obstacle distance approached a significant reduction when compared at matched speed ($t_{10}=2.96, P=.014$).

Some aspects of foot contact were modulated following stroke. Compared with subjects without stroke walking at self-selected speed, subjects with stroke reduced the horizontal velocity at foot contact ($t_{10}=3.85, P=.003$) and tended to land with a flatter foot (reduced angle between the foot and the ground) ($t_{10}=2.76, P=.020$) when leading with the unaffected limb. No differences were detected when leading with the affected limb ($P>.05$). At matched speed, foot angle and foot velocity at landing were not different between groups ($P>.05$).

Inspection of lead-limb joint angles at foot contact suggested that movement patterns used by the 2 groups were similar. Three variables appeared to differ between the groups, as illustrated in Figure 5. There was a trend for subjects with stroke to have greater knee flexion at foot contact in both the affected and unaffected limbs. Compared with subjects without stroke at matched speed, subjects with stroke appeared to have a pelvis that was tilted more anteriorly, particularly as the unaffected limb contacted the ground. The hip also appeared more flexed in subjects with stroke at matched speed.

Figure 5 demonstrates that subjects with stroke were generally more flexed on the stance (trail) limb as the lead foot contacted the ground. Compared with subjects without stroke at self-selected speed, subjects with stroke appeared to have less hip extension in both the affected and unaffected stance limbs. The ankle position of the subjects with stroke tended to be more dorsiflexed, particularly on the unaffected stance limb.

**Trail-Limb Obstacle Clearance**

Toe clearance in the affected trail limb, illustrated in Figure 6, was reduced compared with that of subjects without stroke walking at self-selected speed ($t_{10}=3.17, P=.010$). No differences between groups were detected as the unaffected trail-limb toe cleared the obstacle ($P>.05$).

Examination of kinematic data suggests that subjects with stroke had greater anterior pelvic tilt when compared at matched speed, as illustrated in Figure 6. Subjects with stroke also appeared to increase affected and unaffected trail-limb hip flexion, but reduce affected limb knee flexion. The height of the hip joint of the affected or unaffected stance (lead) limb as the trail limb cleared the obstacle did not differ between the groups at either speed ($P>.05$).
Figure 3.
Lead-limb clearance: (A) illustration of lead limb (bold) at lead-limb clearance, (B) toe clearance, (C) lead-limb pelvic tilt, (D) lead-limb hip abduction, (E) illustration of stance (bold) limb at lead-limb toe clearance, (F) stance-limb hip flexion, (G) stance-limb knee flexion, and (H) stance-limb ankle dorsiflexion. Error bars represent standard deviations. Data corresponding to trials in which the affected limb led are on the left side of all graphs.
As demonstrated in Figure 7, trail-limb post-obstacle distance following stroke was reduced in the affected and unaffected limbs compared with subjects without stroke walking at both speeds (affected limb at self-selected speed: \( t_{(10)} = 5.69, P = .000 \); unaffected limb at self-selected speed: \( t_{(11)} = 5.77, P = .000 \); affected limb at matched speed: \( t_{(10)} = 3.15, P = .010 \); unaffected limb at matched speed: \( t_{(11)} = 3.03, P = .011 \)). The reduction in trail-limb post-obstacle distance was not solely due to reduced lead-limb post-obstacle distance because trail-limb step length also was decreased (affected limb at self-selected speed: \( t_{(10)} = 4.32, P = .002 \); unaffected limb at self-selected speed: \( t_{(11)} = 6.00, P = .000 \); affected limb at matched speed: \( t_{(10)} = 2.39, P = .038 \); unaffected limb at matched speed: \( t_{(11)} = 3.46, P = .005 \)).

Following stroke, horizontal foot-contact velocity of the unaffected trail limb was reduced when compared at self-selected speed (\( t_{(11)} = 3.26, P = .008 \)), but not at matched speed (\( P > .05 \)). Horizontal foot-contact velocity of the affected trail limb did not differ between groups (\( P > .05 \)). At affected and unaffected trail-limb contact, subjects with stroke landed with a flatter foot when compared at self-selected speed, but not at matched speed (affected limb: \( t_{(10)} = 2.91, P = .016 \); unaffected limb: \( t_{(11)} = 3.80, P = .003 \)).

Inspection of lower-limb kinematics suggested that subjects with stroke appeared more flexed on the affected and unaffected trail-limb knees at foot contact, as illustrated in Figure 7. Subjects with stroke were more anteriorly tilted at the pelvis, particularly as the unaffected trail limb contacted the ground. No other differences between groups were observed.

**Temporal Variables**

As illustrated in Figure 8, unaffected lead-limb pre-obstacle and post-obstacle swing time were not altered...
Figure 5.
Lead- and trail-limb kinematics at lead-limb foot contact: (A) illustration of lead (bold) limb at lead-limb foot contact, (B) lead-limb pelvic tilt, (C) lead-limb hip flexion, (D) lead-limb knee flexion, (E) illustration of trail (bold) limb at lead-limb foot contact, (F) trail-limb hip extension, and (G) trail-limb ankle dorsiflexion. Error bars represent standard deviations. Data corresponding to trials in which the affected limb led are on the left side of all graphs.
following stroke. Affected lead-limb pre-obstacle swing time also was not altered. Post-obstacle swing time on the affected lead limb, however, was increased in subjects with stroke compared with subjects without stroke at self-selected speed \((t_{11}=4.88, P=.000)\), and there was a trend for an increased post-obstacle swing time when compared at matched speed \((t_{11}=2.74, P=.019)\).

When the affected limb trailed, pre-obstacle trail-limb swing time tended to be reduced in subjects with stroke compared with subjects without stroke at matched speed \((t_{10}=2.33, P=.042)\). When the unaffected limb trailed, there was a trend for post-obstacle trail-limb swing time to be reduced following stroke at matched speed \((t_{11}=2.90, P=.014)\).
Figure 7.
Trail-limb kinematics at trail-limb foot contact: (A) illustration of trail (bold) limb at trail-limb foot contact, (B) trail-limb post-obstacle distance, (C) trail-limb foot-contact velocity at landing, (D) angle between the trail foot and the floor at foot contact, (E) trail-limb pelvic tilt, and (F) trail-limb knee flexion. Square brackets indicate differences between groups ($P<.0125$). Error bars represent standard deviations. Data corresponding to trials in which the affected limb led are on the left side of all graphs.
Control of the lower limbs during obstacle crossing was abnormal following stroke, whether subjects led with the affected or unaffected limb. The reduced gait speed in subjects with stroke may have accounted for some of the spatial and temporal differences in obstacle crossing observed. For example, affected lead-limb post-obstacle distance (Fig. 4) was reduced compared with subjects without stroke walking at self-selected speed, but not when walking speed was matched. Not all differences between groups were accounted for by reduced walking speed. Following stroke, the affected and unaffected trailing limb landed much closer to the obstacle (post-obstacle distance) compared with subjects without stroke walking at matched speeds (Fig. 7). Although statistical significance was not reached, there also was a suggestion that pre-obstacle and post-obstacle distance of the unaffected lead limb remained reduced and that temporal variables were altered. We believe, therefore, that slower gait speed following stroke accounted for some, but not all, movement abnormalities during obstacle crossing.

Adaptive Modifications to the Movement Pattern of Subjects With Stroke During Obstacle Crossing

Some modifications to the movement patterns of the subjects with stroke may have increased safety during obstacle crossing. Subjects with stroke placed the lead limb closer to the obstacle before crossing, but did not modify trail-limb pre-obstacle placement. Chou and Draganich demonstrated that if the trail limb was positioned too close to the obstacle, trail-limb clearance was reduced and moments of force around the trail ankle during stance increased. This strategy may be difficult to control following stroke. Placing the lead limb closer to

**Figure 8.**

Lead- and trail-limb temporal characteristics: (A) lead-limb pre-obstacle swing time, (B) lead-limb post-obstacle swing time, (C) trail-limb pre-obstacle swing time, and (D) trail-limb post-obstacle swing time. Square brackets indicate differences between groups (P<.0125). Error bars represent standard deviations. Data corresponding to trials in which the affected limb led are on the left side of all graphs.
the obstacle may have contributed to safe obstacle crossing following stroke by assisting with more optimal placement of the trail limb in front the obstacle.

Modifications during landing also may have increased safety of obstacle crossing. Unaffected-limb foot-contact velocity was reduced and the angle between the foot and floor was reduced on both lead and trail limbs, compared with subjects without stroke walking at self-selected speed. These modifications could enhance safety by reducing the risk of a slip on landing.

Lead-limb clearance, however, was not modified to increase safety following stroke. This finding differs from reported results in the previous study, in which subjects with stroke tended to have increased lead-limb clearance. The lead (swing)-limb movement patterns in the subjects with stroke in the current study were remarkably similar to the patterns used by subjects without stroke. Figure 3 illustrates, however, that subjects with stroke were more flexed in the stance limb, although the vertical height of the hip joint was not altered. Similar patterns were observed in both the affected and unaffected stance limbs. Therefore, it does not appear that the pattern can be completely attributed to the unilateral sequelae of a stroke, such as loss of muscle force or sensory disturbance. Post hoc analysis of the lower-limb kinematics during unobstructed gait confirmed a trend for subjects with stroke to be more flexed at the hip and knee during affected- and unaffected-limb stance compared with subjects without stroke. This finding suggests that people with stroke may generally adopt a more flexed posture in the stance phase during walking. We hypothesize that stance-limb flexion may have assisted in balance control. Further examination of the balance-control mechanisms during obstacle crossing is warranted.

Some temporal modifications also may have enhanced safety following stroke. Subjects with stroke increased affected lead-limb post-obstacle swing time compared with subjects without stroke walking at both self-selected and matched speeds. The increased swing time might provide more time to modify placement of the affected leading limb after the obstacle. Control of the affected limb during the landing phase appears to be impaired.

Maladaptive Modifications to the Movement Pattern of Subjects With Stroke During Obstacle Crossing
Safety during obstacle crossing following stroke was compromised by the reduction in post-obstacle distance of the affected and unaffected lead limbs (Fig. 4). Placing the limb closer to the obstacle at landing places a person at risk of actual contact with the obstacle on landing. This behavior was seen in this study and in the previous experiment. This was only partly related to reduced speed following stroke. Increased stance (trail)-limb flexion, which effectively “shortens” the trail limb, combined with increased lead-limb knee flexion at foot contact, which reduces the “reach” of the lead limb may account for some of the reduction in post-obstacle distance.

Safety also may be compromised by the reduction in toe clearance when the affected limb trails the unaffected limb. This pattern may place subjects with stroke at increased risk for a trip, although no subject in this study contacted the obstacle with the trail limb. There was a trend for affected-limb knee flexion to be reduced following stroke, which could result in reduced clearance. Further examination of knee flexion in a larger sample and examination of lower-limb kinetics may be useful in determining whether the reduction in toe clearance was due to reduced or altered power generation following stroke.

Clinical Implications and Future Directions
The results of our study, we believe, have important clinical implications for physical therapists. The findings of this study and the previous study highlight that obstacle crossing is abnormal for many people with stroke, whether they lead with the affected limb or the unaffected limb. Difficulty with obstacle crossing may contribute to increased risk for falls following stroke. The results highlight the importance of considering gait speed when analyzing movement disorders. Understanding movement deficits also may provide the basis for training to improve obstacle crossing following stroke. For example, the results indicate that physical therapists do not need to retrain lead-limb clearance following stroke, but lead-limb placement and affected trail-limb clearance may need attention. This study provides a scientific basis for future clinical investigations.

This study is the first to document affected and unaffected lower-limb kinematics during lead- and trail-limb obstacle clearance following stroke; however, there are limitations. Only a small number of subjects were recruited, and all subjects were able to ambulate without physical assistance or a gait aid. The results, therefore, can be generalized only to this population. The findings are pertinent, however, because this group is most likely to return to community ambulation. The sample was heterogeneous in nature, including 2 subjects with sensory loss, 2 subjects with spatial or sensory neglect, and 2 subjects with visual field deficits. Because this was a preliminary study, we decided to include all subjects with stroke, irrespective of impairments. Future studies with larger subject samples would allow further analysis of various impairments, to provide further insight into the impact of specific deficits on obstacle crossing.
Conclusion
Lead- and trail-limb trajectories during obstacle crossing were abnormal following stroke in both the affected and unaffected limbs. The slow gait speed of subjects with stroke accounted for some, but not all, differences observed during obstacle crossing following stroke. Some modifications, such as the reduced distance between the lead limb on landing and the obstacle and the reduced trail-limb clearance on the affected limb, may increase the risk of instability during obstacle crossing.

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