Research Report

Reactive Balance in Individuals With Chronic Stroke: Biomechanical Factors Related to Perturbation-Induced Backward Falling

Pooja Salot, Prakruti Patel, Tanvi Bhatt

Background. An effective compensatory stepping response is the first line of defense for preventing a fall during sudden large external perturbations. The biomechanical factors that contribute to heightened fall risk in survivors of stroke, however, are not clearly understood. It is known that impending sensorimotor and balance deficits poststroke predispose these individuals to a risk of fall during sudden external perturbations.

Objective. The purpose of this study was to examine the mechanism of fall risk in survivors of chronic stroke when exposed to sudden, slip-like forward perturbations in stance.

Design. This was a cross-sectional study.

Methods. Fourteen individuals with stroke, 14 age-matched controls (AC group), and 14 young controls (YC group) were exposed to large-magnitude forward stance perturbations. Postural stability was computed as center of mass (COM) position ($X_{COM/BOS}$) and velocity ($\dot{X}_{COM/BOS}$) relative to the base of support (BOS) at first step lift-off (LO) and touch-down (TD) and at second step TD. Limb support was quantified as vertical hip descent (Z_{hip}) from baseline after perturbation onset.

Results. All participants showed a backward balance loss, with 71% of the stroke group experiencing a fall compared with no falls in the control groups (AC and YC groups). At first step LO, no between-group differences in $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ were noted. At first step TD, however, the stroke group had a significantly posterior $X_{COM/BOS}$ and backward $\dot{X}_{COM/BOS}$ compared with the control groups. At second step TD, individuals with stroke were still more unstable (more posterior $X_{COM/BOS}$ and backward $\dot{X}_{COM/BOS}$) compared with the AC group. Individuals with stroke also showed greater peak Z_{hip} compared with the control groups. Furthermore, the stroke group took a larger number of steps with shorter step length and delayed step initiation compared with the control groups.

Limitations. Although the study highlights the reactive balance deficits increasing fall risk in survivors of stroke compared with healthy adults, the study was restricted to individuals with chronic stroke only. It is likely that comparing compensatory stepping responses across different stages of recovery would enable clinicians to identify reactive balance deficits related to a specific stage of recovery.

Conclusions. These findings suggest the inability of the survivors of stroke to regain postural stability with one or more compensatory steps, unlike their healthy counterparts. Such a response may expose them to a greater fall risk resulting from inefficient compensatory stepping and reduced vertical limb support. Therapeutic interventions for fall prevention, therefore, should focus on improving both reactive stepping and limb support.

P. Salot, PT, Department of Physical Therapy, University of Illinois at Chicago, Chicago, Illinois.

P. Patel, MPT, Department of Physical Therapy, University of Illinois at Chicago.

T. Bhatt, PT, PhD, Department of Physical Therapy, University of Illinois at Chicago, 1919 W Taylor St (M/C 898), Chicago, IL 60612 (USA). Address all correspondence to Dr Bhatt at: tbhatt6@uic.edu.

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Falls pose a significant threat to individuals with stroke, as they are a leading cause of injury and reduced functional independence and community mobility.[1] Despite achieving independent ambulation, individuals with stroke are at a high risk for falls, not only during the acute phase, but also in the chronic phase.[2] Moreover, falls in community-dwelling individuals with stroke occur frequently from environmental perturbations such as slips and trips.[3] Even though several fall prevention approaches have been implemented in the past,[4,5] the efficacy of these interventions remains undetermined. Hence, in order to reduce fall risk, it is imperative to understand the biomechanical factors associated with falling.

Although falls are multifactorial,[3,6] deficits in reactive balance control in response to external perturbation are postulated as a key factor increasing fall risk.[7,8] The ability to execute a successful reactive (compensatory) stepping response to a large-magnitude perturbation, induced during stance or dynamic activities such as gait, is a must for balance recovery. Previous studies in older adults have shown that, compared with young adults, older adults who fell took a larger number of compensatory (recovery) steps, experienced foot collisions, and had delayed step initiation and a shorter step length.[9,10] Previous studies also have identified 2 key causative factors of slip-related falls that pertain to deficits in reactive control: reduced dynamic center of mass (COM) state (ie, its velocity and position relative to the base of support [BOS]) and inefficient vertical limb support.[11,12] Although there is significant evidence examining kinematics of perturbation-induced reactive responses in healthy young and older adults, there are few studies evaluating these parameters in ambulatory individuals who have chronic stroke.[13]

Recent studies have examined reactive stepping responses to stance perturbations in individuals with stroke.[14–17] The results indicated a preference for stepping with the nonparetic limb under unconstrained situations.[14] Furthermore, physically constraining the preferred stepping limb (mostly nonparetic) could also elicit stepping with the nonpreferred (mostly paretic) limb in some individuals with stroke.[16] These preliminary studies indicate the preserved ability of compensatory stepping responses during stance perturbations in survivors of chronic stroke.

Furthermore, these studies have outlined differences in compensatory stepping for individuals with stroke compared with healthy adults. They have highlighted that factors such as multiple stepping,[16] delayed step onset,[17] and inadequate foot clearance[14,17] lead to falls. However, the biomechanical characteristics of the compensatory stepping response, its correlation to postural stability, and the behavioral outcome (recovery, balance loss, or fall) have not been examined. Because an effective compensatory stepping response is essential to prevent a fall once loss of balance is initiated from a large-magnitude perturbation, it is important to understand the specific characteristics of compensatory stepping responses that may contribute to falls in individuals with stroke.

The aim of our study, therefore, was to examine the effect of stroke on reactive balance control and fall risk in community-dwelling individuals with stroke when exposed to sudden, large-magnitude, slip-like forward perturbations in stance. We hypothesized that, compared with healthy controls, individuals with stroke would demonstrate higher fall risk resulting from a lower postural stability (posterior COM position and slower COM velocity), insufficient vertical limb support (hip height), and an inadequate compensatory stepping response (more steps, delayed step initiation, and decreased step length).

Method

The study included 14 community-dwelling individuals with stroke (stroke group) (43–65 years of age) and 14 age-matched controls (AC group) (47–67 years of age). To examine the predominant effect of stroke, and to rule out any effect of aging, on reactive balance control (as the mean age of the stroke group was 58.4 years and that of the AC group was 58.5 years), a young control group (YC group) (18–31 years of age) was added. The healthy controls were recruited from nearby universities and community centers through flyers. The individuals with stroke were recruited via email and paper advertisements at the local stroke support groups, neurologists' and physicians' offices, and the university hospital. Demographic data for the study participants are presented in the Table.

The inclusion criteria for individuals with stroke were presence of chronic stroke (>6 months) confirmed by the participant's physician, ability to stand independently without any assistive device, and absence of cognitive deficits (>20 on the Short Orientation-Memory-Concentration Test of Cognitive Impairment).[18] The inclusion criteria for the AC group were absence of any self-reported cardiovascular, musculoskeletal, or neurological conditions. The study was conducted in the Physical Therapy Department of the University of Illinois at Chicago. An informed consent statement approved by the university's institutional review board was signed by all the individuals prior to participating in the study.

Protocol

A single slip-like support surface perturbation was induced in the standing position, in the forward direction, using a motorized treadmill (ActiveStep, Simbex, Lebanon, New Hampshire). Prior to each perturbation, participants assumed a comfortable stance position with feet shoulder width apart. A safety harness system attached via ropes prevented participants' knees from touching the treadmill belt in case of fall. A load cell attached between the harness and ropes measured the amount of weight exerted on the safety harness in the downward direction. Without prior knowledge, participants were exposed to a single, large-magnitude forward perturbation at 0.67 m/s for 0.19 m with acceleration of 16.75 m/s^2.[19] They were instructed to execute a natural response to maintain their balance and prevent themselves from falling. We intended to examine the reactive stepping response in individuals with stroke during their natural stance; therefore, we did not correct for initial

Table.
Demographic Data[a]

Variable	Stroke Group (n=14)	Age-Matched Control Group (n=14)	Young Control Group (n=14)
Age (y), $\bar{X}$ (SD) [range]	58.4 (6.1) [43–65]	58.5 (6.2) [47–67]	23.9 (3.7) [18–31]
Sex (male/female)	9/5	6/8	2/12
Weight (kg), $\bar{X}$ (SD) [range]	84.9 (13.3) [68.5–108.9]	80.7 (20.8) [54.9–122.5]	61.4 (10.2) [45.4–83.9]
Body height (cm), $\bar{X}$ (SD) [range]	169.8 (9.6) [157–185.4]	170.3 (10.3) [154.9–185.9]	165.6 (11.2) [152.4–185.4]
Foot length (cm), $\bar{X}$ (SD) [range]	26.5 (2.1) [22.8–29.4]	26.4 (1.45) [24.1–28.6]	24.8 (1.4) [23.5–27.3]
Hemiparetic side (left/right)	2/12	n/a	n/a
Type of stroke		n/a	n/a
Ischemic	8		
Hemorrhagic	5		
Other	1		
Chronicity (years since stroke), $\bar{X}$ (SD) [range]	7.5 (5.6) [1.8–20.1]	n/a	n/a
BBS (/56), $\bar{X}$ (SD) [range]	45.9 (6.89) [30–54]	n/a	n/a
CMSA–leg impairment (/7), $\bar{X}$ (SD) [range]	5 (1) [3–6]		
TUG (s), $\bar{X}$ (SD) [range]	14.78 (2.72) [10.19–16.7]	n/a	n/a

[a] BBS=Berg Balance Scale, CMSA=Chedoke-McMaster Stroke Assessment, TUG=Timed "Up & Go" Test, n/a=not applicable.

weight-bearing asymmetry before perturbation onset.

Data Collection

An 8-camera motion capture system (Motion Analysis Corp, Santa Rosa, California) recording at 120 Hz was used to record full-body kinematics. A Helen Hayes marker set, with 29 markers placed on bilateral bony landmarks, head, and trunk, was used to compute the COM. One marker placed on the treadmill belt was used to identify the perturbation onset. The marker data were low pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. The load cell data were sampled at 1,200 Hz and were synchronized with the motion capture system using an analog-to-digital converter.

In addition to kinematic data, clinical assessment tools were used to measure the level of lower extremity impairment and balance function in the stroke group. The Chedoke-McMaster Stroke Assessment leg impairment score was used to measure lower limb motor impairment, and the Berg Balance Scale and Timed "Up & Go" Test were used to assess balance.

Data Analysis

Perturbation outcomes. Each trial outcome was classified as either (1) a backward loss of balance with a fall or (2) a backward loss of balance with a recovery. A backward loss of balance occurred when a backward compensatory step was initiated in response to forward perturbation and when the stepping limb landed posterior to the stance limb. A trial was classified as a backward loss of balance with a fall if the amount of weight exerted on the safety harness (measured via the load cell) exceeded 30% of the individual's body weight.[12] The other trials with compensatory stepping were classified as a backward loss of balance with recovery. The compensatory stepping response during a fall or recovery was further classified into 3 strategies: (1) a no-step strategy, where the participants did not initiate a compensatory step for recovery; (2) an aborted step (Fig. 1A); or (3) a backward step (Fig. 1B). A step was identified as an aborted step when a compensatory step was initiated by lift-off (LO) of the heel followed by immediate touch-down (TD) without complete clearance of the foot off the treadmill (Fig. 1A).[20] A backward step was identified when the stepping limb's heel demonstrated a clear LO and landed posterior to the nonstepping limb (Fig. 1C).[8] The instance of LO was determined from the Z-coordinate of the heel. Lift-off occurred when the Z-trajectory of the heel marker exceeded 2 standard deviations above the resting baseline position. Lift-off was determined using a customized algorithm and was manually verified by visual inspection. The number of compensatory steps taken to recover balance or terminate into a fall also was recorded.

Postural stability. The COM state (ie, COM position and velocity) was measured relative to the BOS in the anteroposterior direction at LO and TD of the first step and at TD of the second step. At second step TD, the COM state was recorded for the AC and stroke groups, as only 6/14 YC group participants took a second step. The COM position was expressed relative to the rear of the stance limb at LO and relative to the rear of the stepping limb at TD. It was further normalized by the participants' foot length ($X_{COM/BOS}$).[21] The COM velocity was computed as the first-order derivative of COM position and was expressed relative to the velocity of the stance limb heel at LO and relative to the stepping limb heel at TD ($\dot{X}_{COM/BOS}$). It was nor-

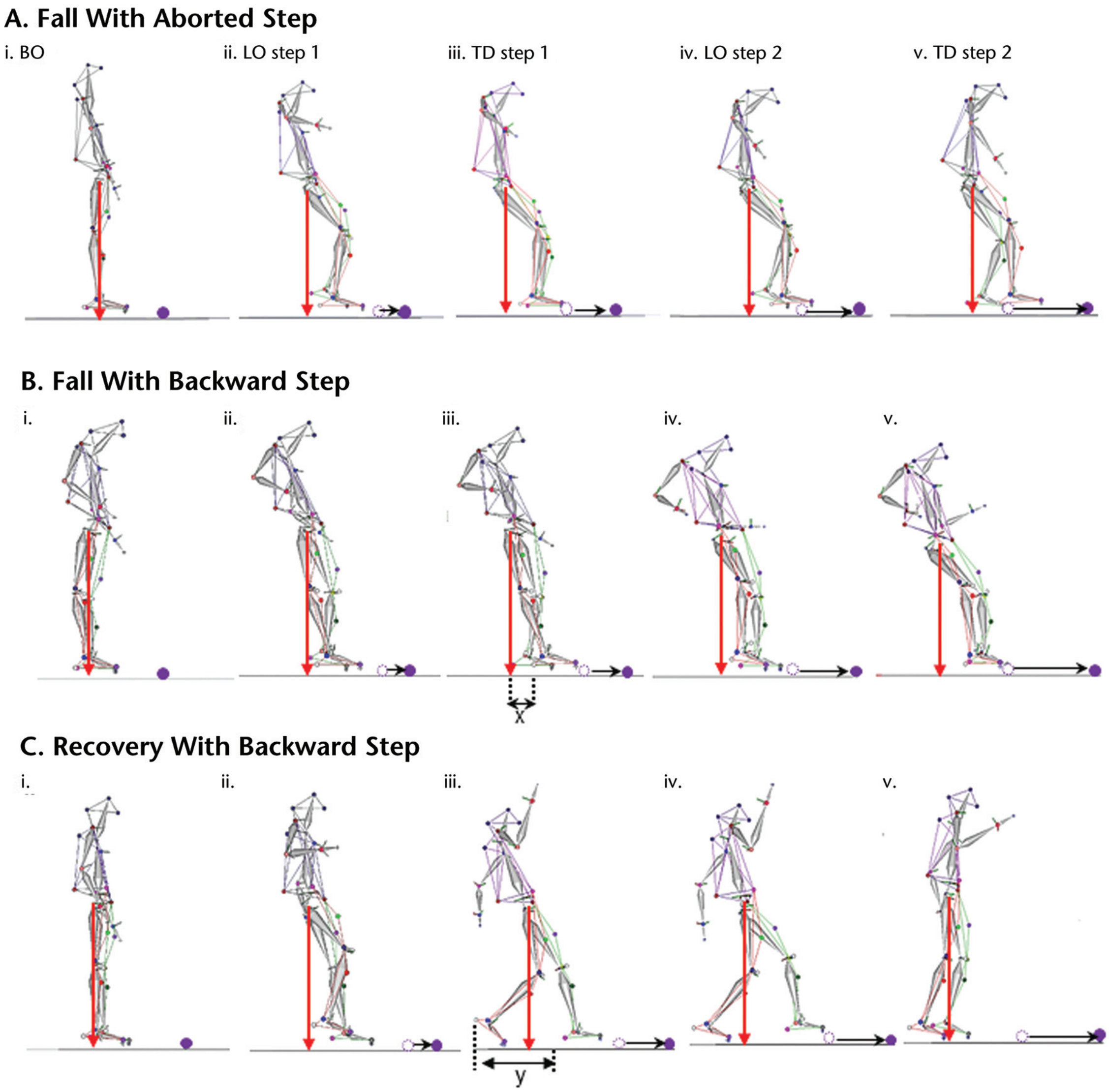

Figure 1.
Motion capture sequence of the slip outcomes and stepping strategies (A–C). The slip outcomes of fall with an aborted step (A) and fall with a backward step (B) are representative of a participant in the stroke group, the slip outcome of recovery with a backward step (C) is representative of a participant in the young control (YC) group. The time events are: (i) treadmill belt movement onset (BO), (ii) lift-off (LO) of first step, (iii) touch-down (TD) of the first step, (iv) LO of the second step, and (v) TD of the second step. In all panels, the empty circle indicates the position of the belt marker at BO, and the arrow represents direction of belt movement. The first backward compensatory step among the stroke group was shorter (denoted by “x” in Fig. B-iii) than that in the YC group (denoted by “y” in Fig. C-iii).

malized to a dimensionless fraction of $\sqrt{gh}$, where g is the acceleration due to gravity and h is the individual’s body height.[22] The time instants of step LO and TD were determined from the Z coordinates of the motion capture data (heel marker).[19]

Temporal and spatial parameters of compensatory step kinematics. To analyze the step kinematics, the compensatory step initiation time (in seconds), execution time (in seconds), step length, and number of compensatory steps required to maintain balance were recorded. The step initiation time was defined as the time taken to LO of the stepping limb heel after perturbation onset. The step execution time was defined as the time elapsed between LO and TD of the stepping limb. The compensatory step length was calculated as the anteroposterior displacement of the stepping limb’s heel from perturbation onset to TD of the stepping limb for first and second steps. It was normalized to the individual’s body height.[19]

Vertical limb support. The hip descent was recorded as the vertical displacement of midpoint of the hip after perturbation onset (Z_{hip}). The midpoint of the hip was determined from bilateral anterior superior iliac spine markers, and the Z_{hip} was normalized by the individual’s body height. The vertical limb support was quantified by measuring maximum vertical hip descent (peak Z_{hip}) relative to that noted prior to perturbation onset.[12]

Statistical Analysis

Proportion of falls, number of steps, and stepping strategies were analyzed using the Kruskal-Wallis test and followed up with the Mann-Whitney U test to resolve the main effect of groups. Although each group comprised 14 participants, the kinematic data for 1 participant in the AC group were unavailable due to technical difficulties (missing markers). Two individuals with stroke showed a no-step response and hence were considered only while reporting perturbation outcome and strategies. As a result, the statistical analysis was performed for 14 YC group participants, 13 AC group participants, and 12 individuals with stroke.

For the first compensatory step, a 3 × 2 repeated-measures analysis of variance (ANOVA) was performed to compare the differences among the groups (YC, AC, and stroke) in postural stability ($X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$) at LO and TD. A post hoc Welch t test (for unequal sample size) was performed to resolve significant main effects and interactions (event × group). A one-way ANOVA was performed to determine the differences among groups in compensatory step kinematics (step initiation time, step execution time, and compensatory length) followed by post hoc Welch t test to resolve significant main effects.

A 2 × 2 ANOVA was performed to compare the differences in postural stability ($X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$) between the stroke group and AC group from first step to second step TD. As not all participants in the YC group initiated a second compensatory step (6/14 in the YC group showed a second compensatory step), their reactive stepping response for the second step was not included in the analyses; however, their data are reported in the Results section. The significant main effects and interactions were resolved using post hoc Welch t test. Furthermore, a Welch t test was performed between the AC and stroke groups to compare the differences in second compensatory step length.

The differences in vertical limb support (peak Z_{hip}) among groups were analyzed using one-way ANOVA and followed up with Welch t test. The significance level for all analyses was set at .05 using IBM SPSS version 20.0 (IBM Corp, Armonk, New York).

Role of the Funding Source

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Results

Perturbation Outcome

Participants in all 3 groups (YC, AC, and stroke) experienced a backward loss of balance, exhibiting either a backward step or an aborted step strategy or a no-step strategy. There was a significant difference in the stepping strategy among the groups (χ^2 [2, N=41]=7.86, $P=.020$). The backward step strategy emerged as the preferred strategy in the YC group (14/14) and for 92% of the participants (13/14) in the AC group; however, a backward step was seen in only 64% of the participants (9/14) in the stroke group ($U=63$, $P=.016$ for the stroke group versus the YC group and $U=64.5$, $P=.076$ for the AC group versus the stroke group). The aborted step strategy was exhibited by 1 participant in the AC group and 3 participants in the stroke group, and 2 individuals with stroke exhibited a no-step strategy. Furthermore, a majority of the individuals with stroke (83.3%, 10/12) initiated the first step with the nonparetic limb.

There was a significant difference in the incidence of falls among the groups (χ^2 [2, N=41]=31.9, $P<.0001$) (Fig. 2A). Post hoc analysis revealed a significantly greater number of falls recorded between the stroke and YC groups ($U=14.00$, $P<.0001$) and the stroke and AC groups ($U=13.00$, $P<.0001$). Out of the 100% backward loss of balance in each group, no participants in the YC and AC groups and 71.4% (10/14) of individuals with stroke experienced a fall. Of all individuals with stroke who experienced a fall, a majority exhibited falling with a backward step (5/10) compared with falling with an aborted step (3/10) and no-step response (2/10). Out of the 4 recoveries seen in individuals with stroke, all exhibited a backward step strategy. Furthermore, the individuals with stroke took significantly more steps ($\bar{X}=2.8$, SD=1.1) compared with the AC group ($\bar{X}=2.1$, SD=0.3) and the YC group ($\bar{X}=1.4$, SD=0.5) ($P<.05$) (Fig. 2B). Of the 12 individuals with stroke who demonstrated a stepping response, 11 took a second step. Of those 11 participants, 9 (81.8%) demonstrated the second step with the paretic limb, and 2 (18.2%) stepped with the nonparetic limb. All 13 AC group participants analyzed initiated a second compensatory step.

First Compensatory Step Response

For the first compensatory step, there was a significant event (first step LO and TD) × group (YC, AC, and stroke) interaction for $X_{COM/BOS}$ ($F_{2,36}=6.09$, $P=.005$) and $\dot{X}_{COM/BOS}$ ($F_{2,36}=6.54$, $P=.004$) (Figs. 3A and 3B). Both the YC and AC groups showed a significantly more positive $X_{COM/BOS}$ (YC group: $P<.0001$, 95% confidence interval [CI]=−1.03, −0.71; AC group: $P<.0001$, 95% CI=−0.82, −0.51) and $\dot{X}_{COM/BOS}$ (YC group: $P<.0001$, 95% CI=−0.14, −0.07; AC group: $P<.0001$, 95% CI=−0.14, −0.06) from first step LO to TD. However, individuals with stroke did not show a significant change in $\dot{X}_{COM/BOS}$ from LO to TD ($P=.102$, 95% CI=−0.6, −0.06). Although there was no difference in $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ among the groups at LO, at TD the $X_{COM/BOS}$ was significantly more anterior in the YC group compared with the stroke group ($P<.0001$, 95% CI=0.37, 0.74) and the AC group ($P<.0001$, 95% CI=0.51, 0.79), with no significant difference among the individuals with stroke and the AC group ($P=.111$, 95% CI=0.20, 0.49). Furthermore, the $\dot{X}_{COM/BOS}$ at TD was significantly more anterior in the YC group ($P<.0001$, 95% CI=−0.05, −0.02) and the AC group ($P<.0001$, 95% CI=−0.06, −0.02) compared with individuals with stroke, with no differences between the other 2 groups ($P=.537$, 95% CI=−0.02, −0.00).

Significant differences in step kinematics were recorded among the 3 groups.

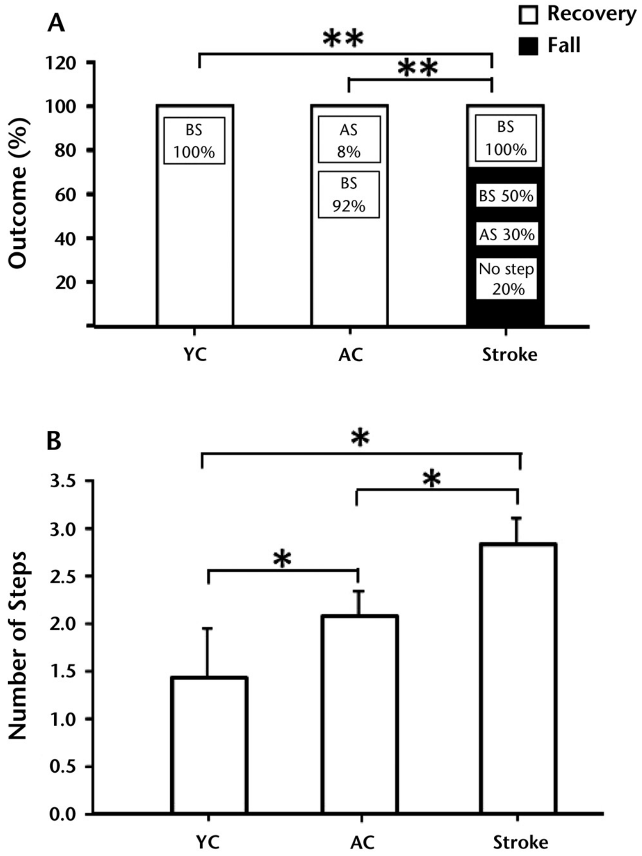

Figure 2.

Percentage of slip outcomes (A) and number of compensatory steps taken (B) for all 3 groups (stroke, young controls [YC], and age-matched controls [AC]). The smaller text boxes within the bars represent the percentage of individuals with an aborted step (AS) or a backward step (BS) strategy and the percentage of individuals showing a no-stepping response during falls and recoveries. Individuals with stroke demonstrated the maximum number of stepping responses, followed by the AC and YC groups. The YC group showed least number of stepping responses to recover balance. Significant differences between groups: $^{*}P<.05$, $^{**}P<.01$.

There was a significant between-group difference for step initiation time ($F_{2,21.6}=5.69$, $P=.010$) and step execution time ($F_{2,22.9}=11.9$, $P<.0001$) (Fig. 3C). The AC and stroke groups demonstrated a significantly delayed step initiation compared with the YC group (AC group versus YC group: $P=.036$, 95% CI=0.19, 0.24; YC group versus stroke group: $P=.003$, 95% CI=0.20, 0.27), with no significant difference between the AC and stroke groups ($P=.181$; 95% CI=0.23, 0.29). The YC group took significantly longer time to complete a step than the AC group ($P<.0001$; 95% CI=0.18, 0.25) and the stroke group ($P<.0001$; 95% CI=0.19, 0.25). There was also a significant difference in the first compensatory step length among all 3 groups ($F_{2,23.2}=7.1$, $P=.004$). The YC group had a longer backward step than the AC group ($P=.041$; 95% CI=0.09, 0.12), along with the AC group having a longer step than individuals with stroke ($P=.047$; 95% CI=0.05, 0.09) (Fig. 3D).

Second Compensatory Step Response

The postural stability ($X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$) for the individuals with stroke differed significantly from the AC group even at second step TD ($X_{COM/BOS}$: $F_{1,22}=41.6$, $P<.0001$, Fig. 4A; $\dot{X}_{COM/BOS}$: $F_{1,22}=15.9$, $P=.001$, Fig. 4B). At second step TD, the individuals with stroke showed a more posterior $X_{COM/BOS}$ ($P<.0001$; 95% CI=0.32, 0.88) and larger backward $\dot{X}_{COM/BOS}$ ($P=.034$; 95% CI=−0.05, −0.00) than the AC group. The AC group showed a significant anterior shift in $X_{COM/BOS}$ from first to second step TD ($P=.001$; 95% CI=−0.90, −0.31), but no significant difference was noted in $\dot{X}_{COM/BOS}$ ($P=.071$; 95% CI=−0.03, −0.00). Furthermore, there was no significant difference in $X_{COM/BOS}$ ($P=.528$; 95% CI=−0.27, −0.50) and $\dot{X}_{COM/BOS}$ ($P=.503$; 95% CI=−0.06, −0.03) between the events within individuals with stroke. The second compensatory step length was also significantly greater in the AC group compared with the stroke group ($P<.0001$; 95% CI=0.14, 0.24) (Fig. 4C). The postural stability and compensatory step length for the young participants who took a second step was as follows: $X_{COM/BOS}=0.677\pm0.44$, $\dot{X}_{COM/BOS}=0.021\pm0.06$, and compensatory step length=0.190±0.13.

Vertical Limb Support

Significant differences in peak Z_{hip} were noted among the 3 groups ($F_{2,22.5}=3.7$, $P=.040$), with the stroke group exhibiting the greatest hip descent from baseline compared with the other 2 groups (YC group versus stroke group: $P=.014$, 95% CI=−0.02, −0.006; AC group versus stroke group: $P=.045$, 95% CI=−0.02, −0.01) (Fig. 4D). In the stroke group, the time of peak Z_{hip} occurrence ($\bar{X}=2.17$ seconds, SD=1.38) was before the instance of the first compensatory step TD ($\bar{X}=2.35$ seconds, SD=1.3), whereas in the AC group, peak Z_{hip} ($\bar{X}=1.40$ seconds, SD=0.27) occurred after the compensatory step TD ($\bar{X}=1.34$, SD=0.07).

Discussion

The aim of the current study was to examine the effect of stroke on fall risk by examining the differences in reactive balance control between community-dwelling individuals with stroke and healthy controls to sudden, large-magnitude, slip-like forward perturbations in stance. As hypothesized, individuals with stroke were at a higher fall risk resulting from a lower postural stability (posterior COM position and larger backward COM velocity relative to BOS), insufficient vertical limb support (lower hip height), and an inadequate compen-

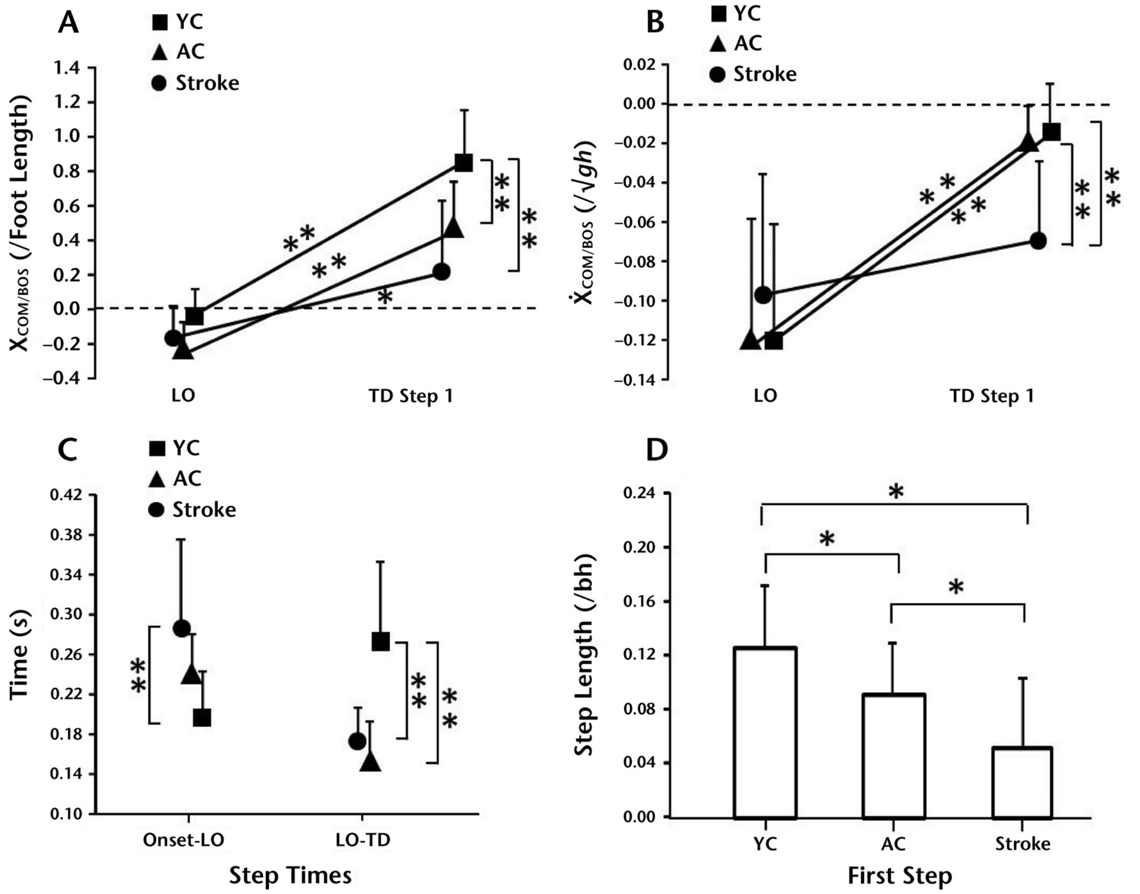

Figure 3.

Mean (SD) differences in postural stability among the 3 groups (stroke, young controls [YC], and age-matched controls [AC]). (A) Center of mass (COM) position relative to base of support (BOS) ($X_{COM/BOS}$) normalized to foot length among all 3 groups at first step lift-off (LO) and touch-down (T), and (B) COM velocity relative to heel velocity ($\dot{X}_{COM/BOS}$) normalized to square root of gravity × height ($\sqrt{gh}$) at first step LO and TD. By first step TD, the YA and AC groups had improved significantly in $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$, but the stroke group remained unstable. (C) Mean (SD) differences in step kinematics among the 3 groups. The stroke group had a delayed step initiation time (time elapsed between belt onset and LO) compared with the YC group and a quick execution time (time elapsed between LO and TD) compared with the AC and YC groups. (D) First step length was significantly smaller for the stroke group compared with both control groups. Significant differences within and between groups: *$P<.05$, **$P<.01$.

satory stepping response (greater number of steps, delayed step initiation, and decreased step length) compared with the healthy controls (AC and YC groups).

Regardless of age, all of the participants experienced a loss of balance following a large-magnitude, slip-like perturbation. This loss of balance was evident from postural instability (ie, COM position outside the posterior margin of BOS [negative $X_{COM/BOS}$] and a larger backward COM velocity relative to BOS [negative $\dot{X}_{COM/BOS}$]) at LO. Upon loss of balance, all participants, except for 2 participants in the stroke group, were able to initiate a compensatory stepping response to recover balance. Despite no difference in loss of balance at LO among the groups, the ability to recover balance profoundly differed in the stroke group compared with the other 2 groups. All the 3 groups had improved postural stability from LO to TD (greater positive $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$) such that the YC and AC groups were remarkably similar in regaining postural stability. The individuals with stroke, however, were more unstable (negative $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$) compared with the healthy controls.

Marked differences among the groups in the stability at TD could be related to the differences in the compensatory step length. Upon loss of balance from a large-magnitude perturbation, a large compensatory step is advantageous to maintain the COM well within the BOS and to generate adequate ground reaction force to reverse backward COM velocity.[23] Compared with the controls, the individuals with stroke demonstrated significantly shorter backward steps (64.28%) or aborted steps (21.4%), making them more unstable (more negative $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$).

Although the AC group equaled the YC group in regaining stability at first step TD (no difference in $X_{COM/BOS}$ and

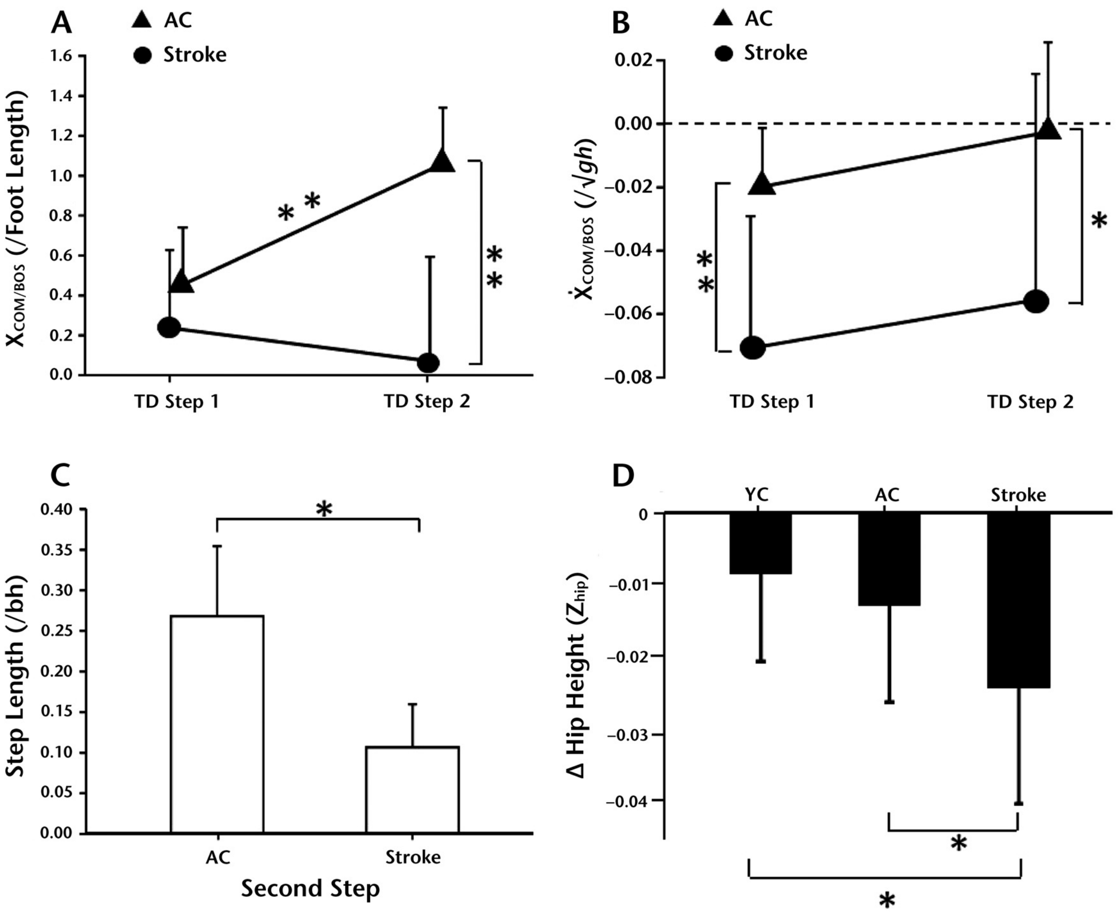

Figure 4.

Mean (SD) differences in (A) center of mass (COM) position relative to base of support (BOS) ($X_{COM/BOS}$) normalized to foot length and (B) COM velocity relative to heel velocity ($\dot{X}_{COM/BOS}$) normalized to square root of gravity × height ($\sqrt{gh}$) between the age-matched controls (AC group) and the stroke group. The AC group showed a significant improvement in $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ by first step touch-down (TD), whereas the stroke group showed a more posterior $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ and was more unstable. Also shown are mean (SD) differences in (C) second compensatory step length and (D) vertical hip descent (Z_{hip}) from preperturbation baseline hip position among the young control (YC), AC, and stroke groups. Significant differences within and between groups: $^{*}P<.05$, $^{**}P<.01$.

$\dot{X}_{COM/BOS}$ between the groups), the AC group was more likely to execute a second compensatory step to recover balance. The first compensatory step for the AC group, although larger than that of the stroke group, was shorter than that of the YC group. The YC group had a more anterior $X_{COM/BOS}$ than the AC group, along with a $\dot{X}_{COM/BOS}$ very close to 0 by first step TD (COM catching up to the heel and moving in same direction at the same speed). Hence, due to this relative state of stability, there might not have been a need to take a second compensatory step. In addition, the fact the young adults executing a single step did not demonstrate any falls further indicates that the first step was sufficient for balance recovery in these individuals. The AC group, however, had a less anterior $X_{COM/BOS}$, requiring the initiation of a second compensatory step. As the AC group comprised individuals in the older age group, it is also possible that age-related decline in reactive balance control along with a fear of falling could have influenced the stepping behavior, resulting in more than one step to recover balance. Previous studies have also reported that older adults execute multiple steps during sudden perturbations[24] and often resort to multiple steps when it is deemed unnecessary.[25]

The AC group showed a larger second compensatory step leading to a more anterior $X_{COM/BOS}$ than at first step TD and a $\dot{X}_{COM/BOS}$ nearing 0, attaining a stable state. Unlike the AC group, which resorted to a larger second step, the survivors of stroke were unable to modulate their step length to assume a more stable position at second step TD, resulting in continued instability even after second step execution (more posterior $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ compared with AC). As the majority of the second step in the stroke group was taken by the paretic limb, it is possible that the existing neuromuscular impairments (Chedoke-McMaster Stroke Assessment mean leg impairment score=5) could have prevented achieving a larger step length.

Apart from the influence of instability, another factor contributing to falls was change in postperturbation vertical limb support. The inability to generate adequate joint moments to reverse the perturbation induced downward descent and restore an upright stance contributes directly to increased fall likelihood.[26] In the current study, the amount of limb support provided to maintain an upright posture was quantified by a simple measure of change in vertical hip height, which has been linearly correlated with vertical ground reaction force. This relationship has been previously demonstrated in studies examining slip-related fall risk in older adults.[12] A forward perturbation not only displaces the COM more posteriorly and farther away from forward moving foot, but there is also a simultaneous descent of pelvis to the ground. Such a descent, if not reversed, would lead to greater knee flexion, restricting the ability to execute a larger step length due to diminished foot clearance, after which a fall is inevitable.

We noticed an initiation of hip descent occurring after perturbation, with individuals with stroke showing greater hip descent (peak Z_{hip}) and thus less vertical limb support compared with the healthy controls. The instance of peak Z_{hip} was after the first compensatory step LO but prior to the first step TD. As a result, the ability to take a longer backward step could be attenuated, leading to emergence of an aborted step strategy. The aborted step strategy has also been shown previously in response to large-magnitude forward slips in young adults at slow walking speeds and older adults and individuals with stroke at their self-selected walking speeds.[13,21] Although this strategy may be used to rapidly re-establish BOS to regain stability, it actually reduces the anteroposterior BOS, increasing the likelihood of a backward balance loss and fall. Thus, due to inadequate limb support combined with either a shorter stepping or aborted step strategy, individuals with stroke showed a higher fall incidence (9/13, 67.23%) compared with the controls (0% in both groups). In contrast to previous studies that showed a high incidence of falls in older adults (40%–42%),[27,28] we did not observe any falls in the AC group. Such a difference in fall incidence could be mainly accounted for by a relatively lower perturbation intensity (displacement and velocity) and middle-aged adults forming the AC group compared with the studies showing falls in older adults.[27,28]

Furthermore, it is important to note that all of the individuals with stroke who exhibited a compensatory step showed a delayed step initiation compared with the control groups. Step initiation necessitates shifting of the body weight onto the nonstepping side in order to unload the stepping limb,[14] and delays in step initiation have been linked with falls.[17] However, after stroke, the weight-bearing symmetry is impaired, with greater weight bearing on the nonparetic limb,[29,30] resulting in a longer time to initiate a step with the more loaded nonparetic limb. Furthermore, due to the decline in weight-bearing ability on the paretic limb during the stance phase,[31] individuals with stroke could have reduced their step execution time to rapidly shift their body weight back onto the nonparetic limb and to re-establish double limb support. This can be suggested from the shorter step execution time observed among survivors of stroke than that in healthy controls.

These findings support the view that impaired reactive balance control to large perturbations may reveal the underlying fall risk, which may not be reflected through performance-based clinical balance assessment tools such as the Berg Balance Scale and Timed "Up & Go" Test.[32] Individuals with stroke who participated in this study were classified as having a low fall risk as demonstrated by scores on the Berg Balance Scale (45.9/56).[33] Despite a low risk of falling, the majority of individuals with stroke experienced a fall upon the sudden forward stance perturbation. As most clinical outcome measures focus on evaluating voluntary balance, reactive balance assessment to large-magnitude perturbations may provide a greater insight into future fall risk, as has been previously demonstrated in older adults.[8,34] So far, most studies examining reactive balance responses in individuals with stroke have reported the characteristics of the first compensatory step. By examining postural stability during the first 2 compensatory steps, this study provides a more comprehensive understanding of the mechanism of fall risk, specifically in individuals with stroke versus young adults and middle-aged adults. Furthermore, a majority of our participants preferred to initiate a compensatory step with the nonparetic limb. Because a real-life slip may occur on either limb, future studies should focus on identifying differences in reactive balance control between the paretic limb and the nonparetic limb.

In summary, survivors of chronic stroke demonstrate a high risk of falls when exposed to sudden, slip-like perturbations compared with their healthy counterparts. Higher fall risk emerges from poor postural stability, inadequate vertical limb support, and inability to execute an effective compensatory step to regain stability upon loss of balance. Although most research is focused on examining biomechanics of the first compensatory step, examining mechanics of the second step might further differentiate fall risk between healthy older adults and people with neurological impairments. It is suggested that in conjunction with restoring independent standing and walking balance, rehabilitation interventions should also target reactive balance training to prevent a fall from an external disturbance, such as that experienced in a real-life situation.

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