

Altered control of postural sway following cerebral infarction

A cross-sectional analysis

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ABSTRACT

Objective: Balance impairment is common following cerebral infarction. However, the effects of lesion hemisphere on postural control are largely unknown. We examined dependence upon vision and noninfarcted regional brain tissue volumes for postural control in individuals with right and left hemisphere middle cerebral artery (MCA) infarcts.

Methods: Subjects with right MCA infarct ($n = 17$, age = 65 ± 8 years, 7 ± 6 years poststroke), left MCA infarct ($n = 20$, age = 65 ± 8 years, 7 ± 6 years poststroke), and controls ($n = 55$, age = 65 ± 8 years) were studied. Postural control was defined by average velocity and the range and variability of mediolateral (ML) and anteroposterior (AP) sway during eyes-open and eyes-closed standing. Regional brain volumes were quantified using anatomic MRI at 3 Tesla.

Results: Right and left hemisphere stroke groups had similar infarct volumes and outcomes. Subjects with right hemisphere infarcts demonstrated greater sway velocity, ML range, and ML variability with eyes closed compared to eyes open. In this group, smaller occipital lobe volumes were associated with greater eyes-open sway velocity ($R = -0.64$, $p = 0.012$) and ML range ($R = -0.82$, $p = 0.001$). Smaller cerebellar volumes were associated with greater eyes-closed sway velocity ($R = -0.60$, $p = 0.015$), ML range ($R = -0.70$, $p = 0.007$), and ML variability ($R = -0.85$, $p < 0.001$). These associations were not observed in left hemisphere infarct subjects or controls. AP sway was unaffected by infarct hemisphere or visual condition and did not correlate with regional brain volumes.

Conclusions: Right hemisphere middle cerebral artery infarcts are associated with increased dependence on vision and noninfarcted brain regions (i.e., occipital lobes, cerebellum) to control postural sway. Strategies emphasizing postural tasks under reduced visual conditions may enhance functional recovery in these individuals. *Neurology*® 2010;74:458-464

GLOSSARY

AP = anteroposterior; DWI = diffusion-weighted image; FLAIR = fluid-attenuated inversion recovery; FOV = field of view; MCA = middle cerebral artery; ML = mediolateral; MP-RAGE = magnetization prepared rapid gradient echo; mRS = modified Rankin Scale; NIHSS = NIH Stroke Scale; TE = echo time; TI = inversion time; TR = repetition time.

Chronic impairment of postural control following cerebral infarction is associated with decreased independence¹ and increased falls.² The postural control system—comprised of the somatosensory, visual, and vestibular sensory systems, numerous brain regions, and the musculoskeletal system³⁻⁵—can often compensate for impairment to one or more of its elements by placing increased dependence upon other, relatively intact elements during daily activities.⁶⁻⁸

Following a stroke, individuals become increasingly dependent upon visual feedback to minimize standing postural sway.^{9,10} Mounting evidence also suggests that localized damage within the right middle cerebral artery (MCA) territory is particularly disturbing to the subjective perception of body “verticality” with respect to gravity only in the absence of visual feedback.^{11,12} This observation suggests that right as opposed to left hemisphere MCA infarction may result in greater dependence on visual feedback for the minimization of standing postural sway.

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Analogous to visual feedback, stroke may also result in greater dependence upon noninfarcted brain regions. MCA supplies the parietal, temporal, and/or frontal lobes.¹³ Following MCA infarct, individuals may therefore exhibit increased reliance on the occipital lobe and cerebellar regions as each are metabolically active during quiet standing¹⁴ and reduced volumes in these regions have been associated with impaired balance in older adults.^{4,15}

We hypothesized that right hemisphere infarct would be associated with increased visual dependence for the minimization of standing postural sway. We further hypothesized that compared to controls, hemispheric infarcts would result in greater reliance upon occipital lobe and cerebellar brain tissue volumes to control postural sway.

METHODS Participants. Community-dwelling men and women more than 6 months after first large vessel hemispheric infarcts affecting less than a third of the MCA territory, as confirmed by examination of radiologic MRI or CT images obtained during the acute phase, were consecutively recruited via community advertisement, the stroke registry, and Beth Israel Deaconess Medical Center records review. Control group subjects were recruited from the community to match the age and sex characteristics of the infarct groups. Neurologic and functional stroke outcomes were assessed by the NIH Stroke Scale (NIHSS) and the modified Rankin Scale score (mRS).¹⁶ All subjects completed the Digit Span test for memory/attention¹⁷ as well as the Rey-Osterrieth Complex Figure test¹⁸ and Clock Drawing test¹⁹ for visuospatial processing ability. Each test was scored using standard procedures.

Exclusion criteria were 1) intracranial or subarachnoid hemorrhage on MRI or CT, 2) any unstable medical condition, 3) vertebrobasilar or carotid disease (not associated with stroke), 4) diabetes mellitus, 5) valvular heart disease or clinically significant arrhythmia, 6) morbid obesity (body mass index >35), 7) self-reported numbness or pain in the feet, 8) inability to stand unassisted with eyes closed for 3 minutes, 9) any metallic bioimplants or claustrophobia, 10) bilateral infarction, and 11) a total NIHSS score >20.

Standard protocol approvals, registrations, and patient consents. This study was approved by the Committee on Clinical Investigations at Beth Israel Deaconess Medical Center and written informed consent was obtained from all subjects.

Procedures. In addition to the aforementioned assessments, standing postural control was examined and MRI was completed during a single visit to the Syncope and Falls in the Elderly laboratory.

Standing postural control. Postural control was examined by measuring body “sway” during quiet standing on a force plate (Kistler Instrument Corp., Amherst, NY). Subjects stood with heels 15 cm apart. Four 1-minute trials were completed: 2 with eyes open and 2 with eyes closed. Rest was provided between each trial.

Center of pressure displacements were recorded at 1,000 Hz using Labview software (Labview 6i, Austin, TX) and filtered with a zero-lag sixth-order Butterworth low-pass filter at 10 Hz. Summary statistics were computed and averaged across trials. The average velocity was computed by dividing total path length by trial duration. Average mediolateral (ML) and anteroposterior (AP) range (mm) was defined as the mean scalar displacement along each principal axis. ML and AP variability (mm) was defined as the SD about each respective mean. In each case, relatively larger values reflected diminished postural control.²⁰

MRI sequences. MRIs were performed on a 3-Tesla GE Signa Vhi scanner using a quadrature and phase array head coils (GE Medical Systems, Milwaukee, WI). High-resolution anatomic images included 3-dimensional magnetization prepared rapid gradient echo (MP-RAGE) (repetition time [TR]/echo time [TE]/inversion time [TI] = 7.8/3.1/600 msec, 3.0 mm slice thickness, 52 slices, bandwidth = 122 Hz per pixel, flip angle = 10°, 24 cm × 24 cm field of view [FOV], 256 × 192 matrix size), fluid-attenuated inversion recovery (FLAIR) (TR/TE/TI = 11,000/161/2,250 msec, 5 mm slice thickness, 30 slices, bandwidth = 122 Hz per pixel, flip angle = 90°, 24 cm × 24 cm FOV, 256 × 160 matrix size), and diffusion-weighted images (DWI) (*b* value of 1,000 s/mm², TR/TE = 10,000/86.6 msec, 5 mm slice thickness, bandwidth = 250 kHz, 128 × 128 matrix size). Image data were saved offline on a CD-RW attached to the scanner.

MRI were analyzed on a Linux workstation using interactive data language tools (Research Systems, Boulder, CO). First, infarct volumes were computed from outlines on T2-weighted FLAIR images and normalized to percent intracranial volume by dividing by intracranial cavity volume and multiplying by 100. Second, brain tissue volumes were calculated from MP-RAGE images using an inherently circular model with spatial normalization within the statistical parametric mapping software package (SPM, University College London, UK). Brain tissue volumes for gray and white matter were segmented and quantified into anatomic regions of interest using the LONI Probabilistic Brain Atlas.²¹ Normalized gray matter, white matter, and brain tissue (gray and white matter summed) volumes in each region were computed by dividing by intracranial cavity volume and multiplying by 100. Although additional brain regions may contribute to postural control,⁴ only the right and left occipital lobes and cerebellum volumes were extracted as each are linked to postural control yet unaffected by MCA infarct.

Statistical analysis. Statistical analyses were performed using JMP software (SAS Institute, Cary, NC). Descriptive statistics were used to summarize all variables. One-way analyses of variance and Student *t* tests examined potential group differences in anthropometrics, cognitive function, stroke severity, and brain region volumes. The effects of right and left hemisphere MCA infarct on postural sway were analyzed by mixed models with group (control, left infarct, right infarct) and condition (eyes open, eyes closed) as between- and within-subject factors. Age, sex, body mass index, and time since stroke were included as covariates. Tukey post hoc analyses were performed where necessary. Linear regression analysis was used to examine relationships between occipital lobe and cerebellar brain tissue volumes and postural sway variables by group, adjusting for the aforementioned covariates. As resolution and contrast issues may confound differentiation of gray and white matter,^{22,23} only regional brain tissue volumes (gray and white matter combined) were included in the present analyses. To control for false positives of the associations between regional brain volumes and dependent

Table Right infarct, left infarct, and control group demographics, stroke characteristics, and occipital lobe and cerebellum volumes (mean ± SD)

	Controls	Left infarct	Right infarct	p Value
Group demographics				
Sex, F/M	34/21	11/9	11/8	—
Age, y	65 ± 8	65 ± 8	65 ± 9	0.88
Height, cm	168 ± 8	169 ± 7	168 ± 9	0.64
Body mass, kg	68 ± 12 ^a	78 ± 15 ^b	77 ± 15 ^b	0.01
Hypertension (self-reported history), %	15	20	26	0.67
Stroke characteristics				
Time since stroke, y	—	7.3 ± 6.9	7.9 ± 5.1	0.72
NIHSS score	—	2.3 ± 0.6	2.8 ± 0.7	0.45
mRS score	—	1.2 ± 0.5	1.4 ± 0.5	0.83
Infarct volume, % ^c	—	1.3 ± 0.5	1.3 ± 0.5	0.94
Cognitive testing (total scaled scores)				
Digit Span	11.1 ± 3.1 ^a	9.8 ± 2.6 ^b	9.9 ± 2.9 ^b	0.01
Rey Osterrieth Complex Figure	19 ± 2	19 ± 4	18 ± 3	0.37
Clock drawing test	7.3 ± 0.9 ^a	6.8 ± .09 ^b	6.6 ± 1.0 ^b	0.01
Normalized brain volumes^c				
Cerebellum brain tissue (%)	8.6 ± 0.9	8.3 ± 1.0	8.5 ± 1.1	0.42
Gray matter (%)	6.1 ± 0.6	5.6 ± 0.6	5.8 ± 0.7	0.16
White matter (%)	2.6 ± 0.2	2.7 ± 0.5	2.7 ± 0.4	0.39
Occipital lobe brain tissue (%)	6.0 ± 0.6	5.9 ± 0.9	5.8 ± 0.8	0.40
Gray matter (%)	3.6 ± 0.1	3.6 ± 0.4	3.5 ± 0.3	0.68
White matter (%)	2.4 ± 0.2	2.2 ± 0.4	2.2 ± 0.3	0.18

Abbreviations: mRS = modified Rankin Scale; NIHSS = National Institutes of Health Stroke Scale.

^{a,b}Homogeneous groups within each row. Means with different letters are significantly different from each other.

^c(Regional volume/intracranial cavity volume) × 100.

variables, a Sidak correction for multiple comparisons adjusted for high correlations within postural sway variables was used (alpha = 0.016).^{24,25}

RESULTS Subject characteristics. Of the 172 subjects consecutively screened, 110 were deemed eligible and 94 completed all assessments included in the current analysis. Demographic characteristics were largely similar among the right infarct group, left infarct group, and controls (table). Infarct groups had greater body mass compared to controls ($p = 0.01$). Subjects with right and left hemisphere infarcts had similar infarct volumes, NIHSS and mRS scores, and time since stroke. Compared to controls, both right and left infarct groups demonstrated reduced performance on the Digit Span (memory/attention) and Clock Drawing (visuospatial ability) cognitive tests ($p = 0.01$). Right and left hemisphere infarct groups did not differ from one another in cognitive test performance. Regional tissue volumes (gray matter, white matter, combined) of the occipital lobes and

cerebellum were similar between groups (table). The brain tissue volumes of the right and left hemispheric regions of the occipital lobes and cerebellum were also similar across groups.

Effects of MCA infarct hemisphere and visual feedback on postural sway. Subjects with right hemisphere infarct had greater sway velocity ($F_{3,89} = 8.4, p = 0.001$), ML range ($F_{3,89} = 5.3, p = 0.007$), and ML variability ($F_{3,89} = 6.8, p = 0.002$) as compared to subjects with left hemisphere infarct and controls. Subjects with left hemisphere infarct and controls did not differ from one another. Group effects were not observed for either AP sway variable.

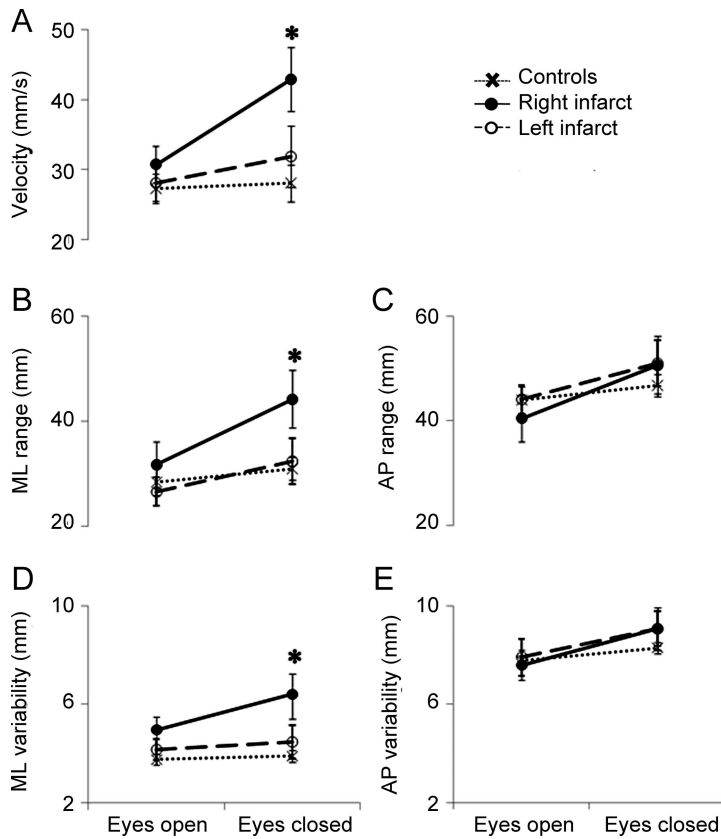
Visual condition influenced sway velocity ($F_{2,90} = 4.9, p = 0.015$), ML range ($F_{2,90} = 8.2, p = 0.006$), ML variability ($F_{2,90} = 6.5, p = 0.01$), and AP range ($F_{2,90} = 6.1, p = 0.014$). In each case, postural sway values were larger with eyes closed.

Interactions were observed between group and visual condition for sway velocity ($F_{2,88} = 16.1, p < 0.001$), ML range ($F_{2,88} = 7.5, p = 0.001$), and ML variability ($F_{2,88} = 4.2, p = 0.01$). For each variable, groups exhibited similar values with eyes open. The left hemisphere infarct and control groups demonstrated similar values across visual conditions. Subjects with right hemisphere infarct demonstrated greater sway velocity, ML range, and ML variability when standing with eyes closed as compared to eyes open, as well as compared to the left hemisphere infarct and control groups in either visual condition (figure 1). Interactions were not observed for either AP sway variable.

Noninfarcted brain tissue volumes and postural sway. Pairwise correlations between occipital lobe or cerebellar brain tissue volumes and postural sway variables were computed with subjects separated by group. Only those correlations reaching significance ($p < 0.016$) are reported. As relationships between postural sway and occipital lobe tissue volumes were similar whether using right lobe, left lobe, or total tissue volumes, only total volumes are reported. Inclusion of potential covariates did not significantly affect reported results.

In subjects with left hemisphere infarct and controls, occipital lobe and cerebellar brain tissue volumes did not correlate with any postural sway variable. In subjects with right hemisphere infarcts, however, correlations between these brain tissue volumes and specific postural sway variables were observed. When standing with eyes open, smaller occipital lobe brain tissue volumes were associated with faster sway velocity ($R = -0.64, p = 0.01$) and greater ML range ($R = -0.82, p = 0.001$). When standing with eyes closed, smaller cerebellar brain tissue

Figure 1 Effects of infarct hemisphere and visual condition on postural sway (mean \pm standard error)



The effects of chronic lesion due to right and left middle cerebral artery infarct on standing sway velocity (A), mediolateral (ML) range (B), anteroposterior (AP) range (C), ML variability (D), and AP variability (E). Interactions ($p < 0.01$) were observed for sway velocity, ML range, and ML variability. For each variable, groups had similar sway when standing with eyes open. The left hemisphere infarct and control groups demonstrated similar sway across visual conditions. The right hemisphere infarct group demonstrated exaggerated sway when standing with eyes closed as compared to eyes open, as well as compared to the other groups under either visual condition. Neither stroke nor visual condition influenced AP sway.

volumes were associated with faster sway velocity ($R = -0.60, p = 0.015$), greater ML range ($R = -0.70, p = 0.007$), and greater ML variability ($R = -0.85, p < 0.001$). Figure 2 illustrates these correlations, in terms of ML range, as compared to subjects with left hemisphere infarcts and controls. Brain tissue volumes of these regions did not correlate with AP sway variables extracted from either visual condition.

DISCUSSION Chronic lesions due to right or left hemispheric infarct did not affect postural sway when standing with eyes open. When standing with eyes closed, subjects with right hemisphere infarct demonstrated exaggerated sway velocity and ML range and variability as compared to both subjects with left hemisphere infarct and controls. These results support our hypothesis that chronic lesions due to right hemisphere MCA infarct result in increased

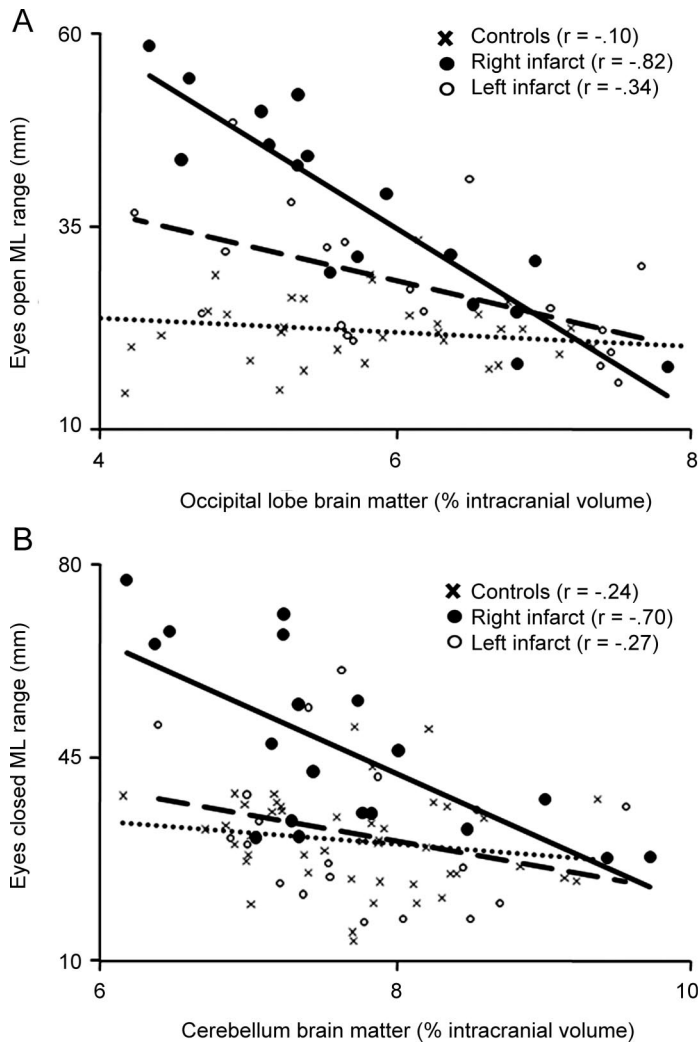
dependence of visual feedback for the minimization of standing postural sway.

Distinct, group-specific correlations were observed between occipital lobe and cerebellar brain tissue volumes and postural sway variables. In the control group and in subjects with left hemisphere infarcts, neither regional brain tissue volume correlated with postural sway. Within subjects with right hemisphere infarcts, those with smaller occipital lobe brain tissue volume tended to have faster sway velocity and greater ML range when standing with eyes open. Those with smaller cerebellar brain tissue volume tended to have faster sway velocity and greater ML range and variability when standing with eyes closed. Therefore, the hypothesis that hemispheric infarcts result in increased dependence upon noninfarcted regional brain tissue volumes was partially supported—it only held for the control of sway velocity and the magnitude of sway in the ML direction in subjects with right hemisphere infarcts.

Chronic right hemisphere MCA infarctions resulted in exaggerated postural sway only in the absence of visual feedback. The capacity to reduce sway velocity and ML magnitude to that observed in controls when visual feedback was present suggests increased dependence upon vision as a main source of sensory feedback to maintain postural sway. These results suggest that functional difficulties and fall risk may be exaggerated in low light environments, and are supported by multiple studies reporting increased postural sway only while standing under conflicting or absent visual feedback conditions in patients with chronic lesions due to mild to moderate stroke.^{9,10} However, these previous studies did not examine the influence of lesion hemisphere and/or did not measure both AP and ML sway. The current results thus extend existing research and suggest that increased visual dependence following MCA infarct primarily occurs within individuals with chronic right hemisphere infarcts, and is primarily limited to the control of ML postural sway.

One potential mechanism underlying exaggerated ML sway during eyes-closed standing in subjects with right hemisphere infarcts may be that the right hemisphere has a predominant role in the control of vertical orientation of the body.^{10,11,26} In individuals with chronic lesions secondary to stroke, infarct hemisphere does not appear to affect the subjective perception of frontal plane (i.e., ML) visual verticality (obtained with eyes open). On the other hand, right (as compared to left) hemisphere lesions are more detrimental to the subjective perception of postural verticality (obtained with eyes closed).^{11,26} This supports our current observation that subjects with

Figure 2 Relationships between noninfarcted brain volumes and postural sway



Scatterplots of occipital lobe brain volume vs mediolateral (ML) sway range during standing with eyes open (A), and cerebellar volume vs ML sway range during standing with eyes closed (B). Linear best-fit lines have been added to the right hemisphere infarct group (solid), left hemisphere infarct group (dashed), and control group (dotted).

right hemisphere infarcts stood with normal ML sway in the presence of visual feedback. However, when standing with eyes closed, and thus forced to rely on a faulty internal perception of postural verticality, exaggerated ML sway was observed (figure 1). Future research is therefore needed to establish the link between visual dependence for postural control and perception of verticality.

Emergent MRI research has linked mobility and balance declines in older adults with sulcal widening and white matter hyperintensities,¹⁵ as well as reduced regional brain tissue volumes of the cerebellum and cerebral cortex.⁴ The present study employed volumetric analysis to examine dependence upon largely intact CNS elements of the postural control system following localized stroke-induced brain damage.

In the control group and in subjects with left hemisphere infarct, occipital lobe and cerebellar brain tissue volumes did not correlate with the magnitude or variability of postural sway. This result suggests that for these individuals, the control of standing postural sway does not depend upon occipital lobe and cerebellar brain tissue volumes. However, as it has been reported that older adults unable to “tandem stand” for 10 seconds had smaller cerebellar volumes compared to nonimpaired individuals,⁴ dependence upon regional brain volumes for postural control is likely contingent upon task difficulty.

In subjects with right hemisphere infarcts, strong correlations were observed between postural sway and both occipital lobe and cerebellar brain tissue volumes. First, those with smaller occipital lobe brain tissue volumes tended to have faster sway velocity and greater ML range when standing with eyes open. As the occipital lobe is the primary visual processing center of the brain,²⁷ this result provides novel evidence for heightened reliance on visual feedback to minimize postural sway when standing under normal visual conditions. Second, right hemisphere infarct patients with smaller cerebellar tissue volume tend to have faster sway velocity and greater ML range and variability when standing with eyes closed. The observation that changing the task—from eyes-open to eyes-closed standing—altered the brain region associated with postural sway provides evidence at the CNS level in support of task-specific postural control.²⁸

Significant correlations between noninfarcted regional brain volumes and postural sway suggest that the brain reserve hypothesis^{29,30} may apply to the postural control system. Brain reserve is defined as the capacity to tolerate age- and/or disease-related changes within the brain without developing clinical signs or symptoms.²⁹ Figure 2 reveals that when compared to controls, not all subjects with right hemisphere infarcts demonstrated exaggerated postural sway during eyes-open standing. Moreover, infarction tended to have less of an effect on postural sway in those with larger occipital lobe tissue volumes. Thus, it may be argued that subjects tended to better tolerate right hemisphere infarct, in terms of standing postural sway, if their noninfarcted regional brain volumes were relatively large. Alternatively, larger occipital volume may be a sign of plasticity-related enhancement of existing pathways during long-term recovery poststroke. While speculative, the possibility of brain reserve for postural control has several implications. For instance, pathologic conditions such as hypertension and diabetes mellitus are each risk factors of stroke³¹ and are associated with diffuse brain tissue atrophy and white matter degenera-

tion.^{32,33} Relatively worse functional outcomes following stroke in these patients³⁴ may therefore stem from reduced brain reserve, and thus, diminished capacity to tolerate stroke-induced brain tissue damage, thus contributing to a less favorable recovery.

This study examined dependence upon unaffected elements of the postural control system in individuals with chronic MCA infarction. Despite the strength of observed correlations, the reader is cautioned against the study's relatively small sample size. Future large-scale longitudinal studies are therefore warranted, especially as the current cross-sectional observations do not delineate between differential effects of localized hemispheric brain damage and the subsequent recovery/adaptation to such damage. Furthermore, conclusions may not generalize to lesions outside the MCA territory, and studies are needed to examine the influence of lesions to specific regions within this territory. Finally, altered dependence on the occipital lobes and cerebellum for postural control was based upon regional volumetric properties of the brain. While positively correlated with perfusion characteristics³⁵ and chronic activity,³⁶ studies examining direct measures of metabolic activity within specific brain regions during standing in this population are warranted.

AUTHOR CONTRIBUTIONS

Statistical analysis was conducted by Dr. Brad Manor and Dr. Vera Novak.

DISCLOSURE

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