Postural orientation with conflicting visual and graviceptive cues to 'upright' among individuals with and without a history of post-stroke 'pushing'

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A. Mansfield[1–3], B. Taati[1,2], C. J. Danells[1,2], L. E. Fraser[1,4], L. R. Harris[4], Jennifer L. Campos[1,2,4]

1 *Toronto Rehabilitation Institute, University Health Network, Toronto, ON, Canada*
2 *University of Toronto, Toronto, ON, Canada*
3 *Evaluative Clinical Sciences, Hurvitz Brain Sciences Program, Sunnybrook Research Institute, Toronto, ON, Canada*
4 *Centre for Vision Research, York University, Toronto, ON, Canada*

Abstract

Purpose: This study aimed to determine how people with stroke, with and without pushing behaviour, use sensory cues to control postural orientation.

Methods: Eight people with chronic stroke (4 with history of pushing behaviour), 5 people with sub-acute stroke (1 with active pushing behaviour) and 8 similarly-aged controls with no history of stroke participated. Participants sat in a motion platform while viewing a 240-degree screen upon which a city street scene was projected. Postural orientation (shoulder and trunk angles) was measured relative to the direction of gravity during 6 trials: visual scene tilted 18-degrees left and right; motion base tilted 18-degrees left and right; and both visual scene and motion base tilted 18-degrees left and right.

Results: Participants with stroke did not appear to adjust their posture in response to visual scene tilt to a greater extent than control participants. For most conditions, chronic stroke participants with a history of pushing behaviour oriented their posture more towards the contralesional side than controls. When the motion base was tilted, sub-acute participants with no evidence of pushing behaviour oriented their posture more in the direction of motion base tilt than controls (e. g., when the motion base tilted to their ipsilesional sides, their trunks and shoulders were oriented to the ipsilesional side).

Conclusion: This study did not find evidence that people with stroke with and without a history of pushing behaviour rely more on static visual cues to control postural orientation than people without stroke.

Keywords: posture, gravity perception, visual perception, kinematics, spatial orientation, stroke

Introduction

Post-stroke pushing behaviour is characterised by postural lean to the contralesional side, despite significant weakness on that side, and resisting correction to upright [16]. To try understand the mechanisms underlying post-stroke pushing, Karnath et al. seated people with and without post-stroke pushing securely in a padded chair that could tilt left or right [10]. With eyes closed, participants were tilted in one direction, and directed the experimenter to move the chair in the opposite direction until they felt upright. The subjective postural vertical is the position relative to the direction of gravity (i. e., earth vertical) at which participants feel upright [4]. One would expect those with pushing behaviour to feel upright when aligned to the contralesional side, as this reflects clinical presentation. However, people with pushing behaviour felt upright when oriented approximately 18° to the ipsilesional side [10]. The authors speculated that the clinical presentation of pushing behaviour reflects compensation for a mismatch between perceived visual and truncal graviceptive cues to upright [10].

The unexpected finding of an ipsilesional bias in subjective postural vertical has been replicated by some [3] but not other [19] subsequent studies. Pérennou et al. observed ≥ 6° contralesional bias in subjective postural vertical among those with pushing behaviour [19]. We observed that people with chronic stroke can continue to have a contralesional bias in subjective postural vertical despite resolution of obvious pushing behaviour [14]. This work [14, 19] suggests that pushing behaviour arises from misperception of body orientation relative to earth vertical, and that people with pushing align their bodies with perceived vertical (i.e., the contralesional side).

While the direction of bias is controversial, evidence suggests that people with pushing behaviour have impaired perception of vertical. The link between impaired perception and behaviour (i.e., natural postural orientation) is less clear. This study aimed to determine how people with stroke use sensory cues to control postural orientation. We seated participants in a 6-degree of freedom motion base with projected visual surround and measured participants' natural posture when the motion base was tilted left and right, and when presented with conflicting and consistent visual cues to earth vertical.

Methods

Participants

Eight participants with chronic stroke, 5 participants with sub-acute stroke and 8 similarly-aged participants with no history of stroke were recruited. Participants were excluded if they had musculoskeletal or neurological conditions (besides stroke) that affect balance, history of vestibular disorders, and/or poor corrected or uncorrected visual acuity. Participants with stroke were excluded if they had bilateral strokes. On item C of the Scale for Contraversive Pushing (SCP [10], resists correction) 4 chronic stroke participants scored ≥ 1 early in stroke recovery; these participants formed the history of pushing (HP) group. The remaining 4 chronic stroke participants had no documented history of post-stroke pushing and formed the no history of pushing (NHP) group. Four sub-acute stroke participants had no evidence of history of pushing behaviour and formed the no-active pushing group (NAP). One sub-acute stroke participant had active pushing behaviour (AP), as assessed by his treating physiotherapist; the SCP could not be assessed for this participant due to his severe postural impairment. Participant characteristics are shown in **Table 1**. The study was approved by the institution's Research Ethics Board and participants provided written informed consent.

Table 1: Participant characteristics. Values are presented for individual participants with stroke. Data for controls are means with standard deviations in parentheses

Participant/ group	Age (years)	Sex	Time post-stroke (months)	Stroke type	Stroke location	NIH-SS (score)	CMSA-leg (score)	CMSA-foot (score)	BBS (score)	SNAP (score)	Left heel touch threshold (log force)	Right heel touch threshold (log force)
Controls	64.1 (7.0)	4 M 4 F	–	–	–	0 (0)	7 (0)	7 (0)	55.9 (0.4)	0.4 (1.1)	4.38 (0.22)	4.24 (0.27)
NHP group												
NHP-1	66	F	7.3	Ischemic	Left basal ganglia	2	6	6	53	0	3.61	3.61
NHP-2	49	F	15.4	Ischemic	Right pons	2	5	5	55	0	3.61	3.84
NHP-3	62	F	17.0	Ischemic	Left internal capsule	1	7	7	56	2	4.08	4.31
NHP-4	58	M	12.2	Ischemic	Right internal capsule	1	7	7	56	7	5.07	4.31
HP group												
HP-5	80	M	44.1	Hemorrhagic	Right thalamus	1	5	4	37	0	4.93	4.93
HP-6	66	M	48.9	Ischemic	Right parietal & frontal	8	3	2	26	33	2.83	4.08
HP-7	79	F	15.6	Ischemic	Right parietal & internal capsule	4	5	5	37	60	*	*
HP-8	78	F	15.5	Ischemic	Right parietal & frontal	2	4	5	29	6	5.07	5.88
NAP group												
NAP-9	64	M	2.5	Ischemic	Right internal capsule & pons	4	5	3	41	0	4.31	4.17
NAP-10	73	F	1.2	Ischemic	Left brainstem	2	6	7	45	4	4.74	4.56
NAP-11	79	F	0.7	Ischemic	Right basal ganglia	3	4	5	29	0	5.18	4.56
NAP-12	60	M	0.6	Ischemic	Cerebellum & right medulla	1	5	5	30	0	3.84	3.61
AP participant												
AP-13	67	M	0.8	Ischemic	Left middle cerebral artery/anterior cerebral artery region	9	3	2	8	0	4.17	4.08

AP active pushing; **BBS** Berg Balance Scale; **CMSA** Chedoke-McMaster Stroke Assessment; **F** female; **HP** history of pushing; **M** male; **NIH-SS** National Institutes of Health stroke scale; **NAP** no active pushing; **NHP** no history of pushing; **SNAP** Sunnybrook Neglect Assessment Procedure; *Unable to assess (participant did not understand the instructions)

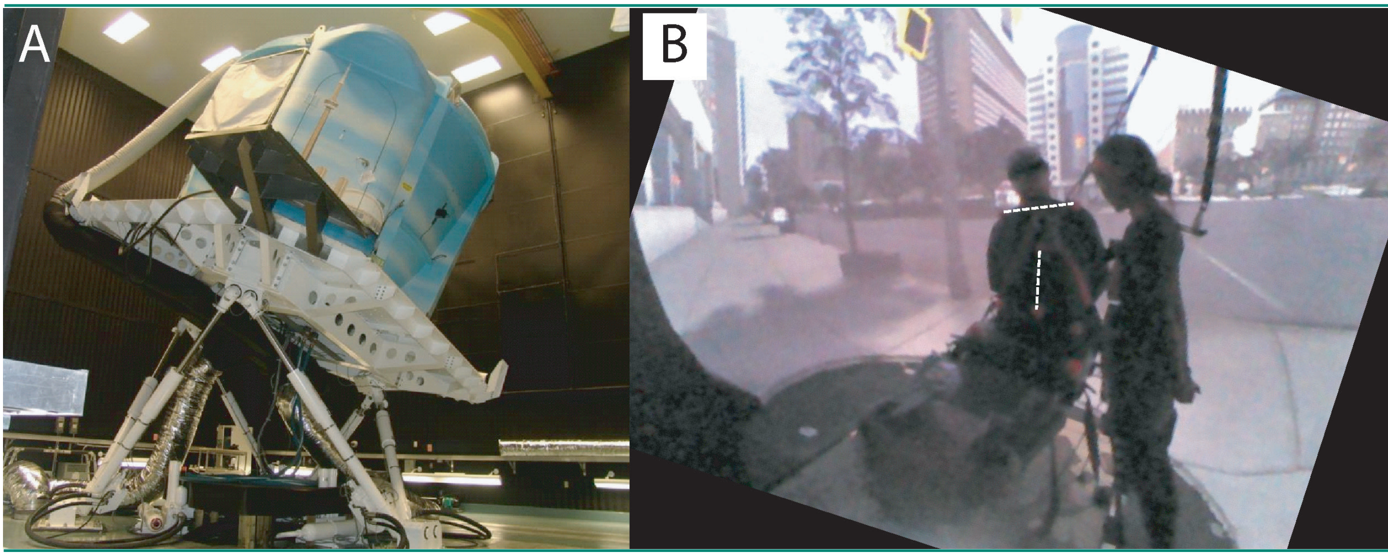

Fig. 1: Motion base and calculation of trunk and shoulder angles. Panel A shows the exterior of the 6-degree of freedom motion base. Panel B shows the view from the digital video camera within the motion base during an M-right trial (see also Figure 2). The orientation of the trunk and the shoulders are indicated by the dotted lines. Note that the image in Panel B has been rotated 18 degrees to the right; earth vertical (i.e., the direction of gravity) is up-down with respect to both images. Trunk and shoulder angles were calculated relative to earth vertical/horizontal.

Procedures

This paper presents a subset of data from a larger study; further details of study procedures not presented here can be found in companion papers [8, 14]. Cutaneous sensation at the plantar surface of the heel was assessed using Semmes Weinstein monofilaments [15].

To assess postural orientation in response to visual and gravitational stimuli, participants were seated on a plinth, placed inside a motion simulator with a 240° horizontal field-of-view projection screen **(Figure 1)**. A non-slip mat (Dycem, Bristol, United Kingdom) was placed on the seat to prevent participants from sliding. A research assistant stood beside participants (out of view) to provide instructions and physical assistance, if required. Both the research assistant and participants wore a harness attached to an overhead support as an extra safety measure. Participants' feet hung freely and they were asked to place their hands on their laps; they were otherwise free to adopt a natural posture. Participants viewed a static city street scene projected on the screen **(Figures 1 & 2)**; the scene had several cues to upright, e.g., sky in the upper portion of the scene, tall buildings [9]. Spherical markers were placed at the approximate locations of the T7 and L5 vertebrae on the back, and on the acromion processes. A digital video camera (sample frequency: 30 Hz) directly behind participants captured the position of these markers in order to calculate trunk and shoulder angles.

Six trials were completed in an unpredictable order **(Figure 2):** visual scene tilted left or right (V trials);motion base tilted left or right (M trials); and both motion base and visual scene tilted left or right (VM trials). Each trial started with the motion base and visual scene oriented upright with respect to earth vertical. Participants were instructed to look straight ahead and to maintain an upright posture. The motion base and/or visual scene then tilted to the right or left at a peak angular velocity of 0.5°/s and acceleration/deceleration of 0.2°/s² until the visual scene and/or motion base was 18° from earth vertical. The motion base and/or visual scene remained static at this angle for 5–10 seconds, and then returned slowly to upright before the next trial.

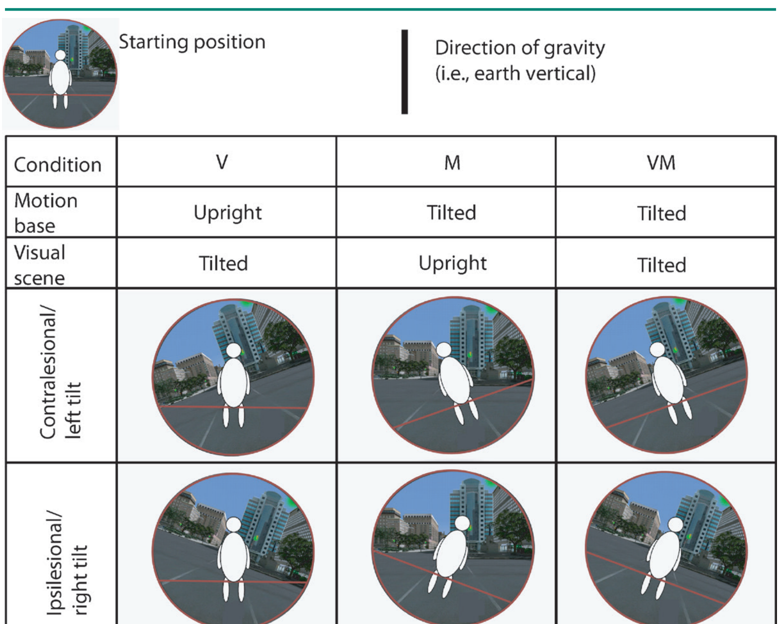

Fig. 2: Illustration of the motion and visual scene condition used in the study. The participant initially sat upright in the motion simulator (starting position). During each trial, the visual scene and/or motion base was tilted 18° to the right or left with respect to the direction of gravity (i.e., earth vertical). The final visual scene/motion base position is illustrated in the figure.

Data processing

Trunk and shoulder angles were calculated for five frames at the start of each trial and when the motion base/visual scene reached the maximum angle using a custom routine implemented in Matlab (R2014a, The Mathworks, Natick, MA, USA). As the camera was placed inside the motion simulator and rotated with the motion base, angles were initially calculated relative to the motion base; the motion base angle was subtracted from the trunk/shoulder angle in order to calculate all angles relative to earth vertical/horizontal **(Figure 1)**. The sign of the angle was changed such that positive angles indicated lean to the ipsilesional side (right for controls), and negative angles indicated lean to the contralesional side (left for controls).

Statistical analyses

As there was only one AP participant, this individual was excluded from statistical analyses. Shapiro-Wilk test was used to confirm that data were normally distributed. Two-way repeated measures analyses of variance (ANOVAs) were used to examine between group responses to each condition. The dependent variables were trunk and shoulder angles, relative to earth vertical/horizontal. The two factors in the ANOVAs were group (control, NHP, HP, NAP) and condition (conflicting or consistent visual cues to vertical). The first ANOVAs compared conditions with the motion base upright with respect to earth vertical; i.e., the conditions were the start position and V trials. The second ANOVAs compared conditions with the motion base tilted; i.e., the conditions were M and VM trials. The group-by-condition interaction effect was used to determine if one group responded differently to a condition than others. In the event of significant interaction or main effects, pre-planned contrasts were used to determine if each stroke group (NHP, HP or NAP) differed from controls. ANOVAs were conducted separately by direction of visual scene/motion base tilt (ipsilesional/right or contralesional/left). Alpha was 0.05 for all analyses.

Results

Missing data

Due to technical difficulties, one NAP participant did not complete the VM contralesional trial; the M contralesional trial was also removed from the analyses for this participant.

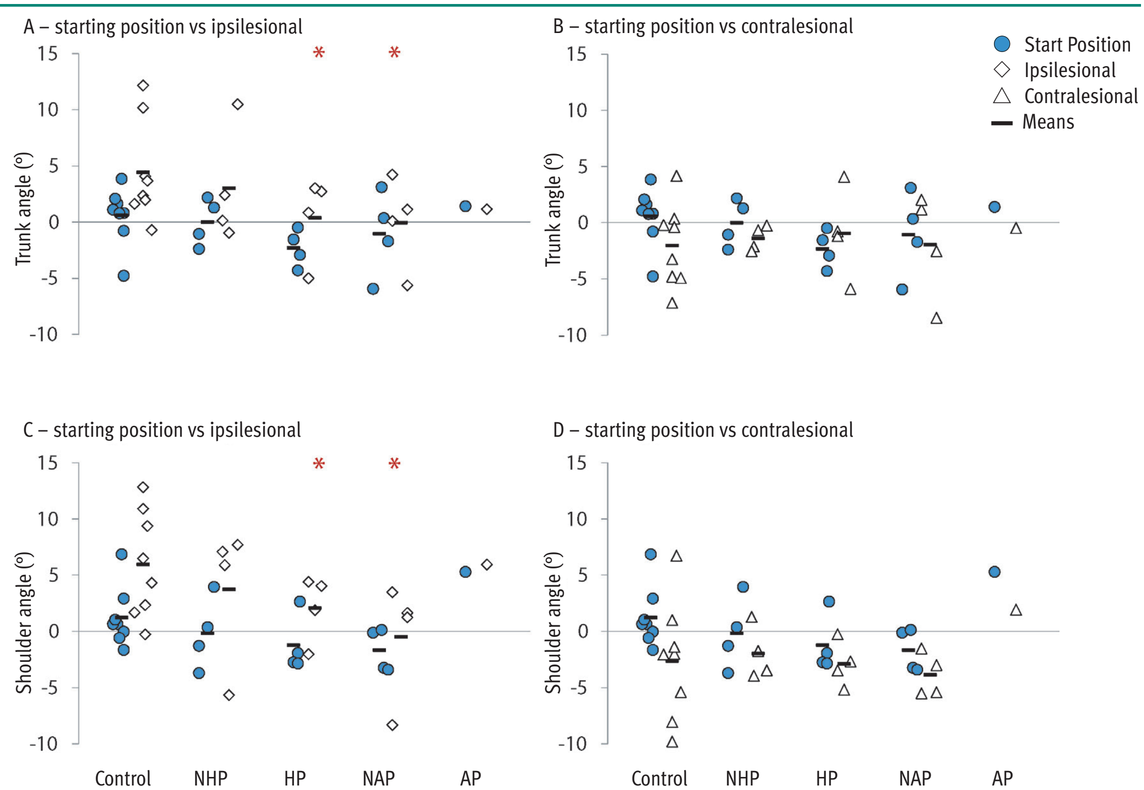

Fig. 3: Trunk and shoulder angles for trials where the motion base remained upright. Panels A and B show trunk angles, and Panels C and D show shoulder angles. Values shown are data points for individual participants, with group means indicated by the black bars. Data points are 'jittered' along the x-axis to prevent overlap of points. Angles were calculated with respect to earth vertical/horizontal, with positive angles indicating orientation to the ipsilesional/right side, whereas negative angles indicate orientation to the contralesional/left side. Data are shown for the V conditions and the starting position (see also **Figure 2**). Significant group effects are indicated with asterisks, where the groups significantly differed from the control group. There were no significant group-by-condition interactions or significant condition effects for these conditions.

Motion base upright

Figure 3 shows the results for trials where the motion base was upright; there were no significant group-by-condition interactions for trunk or shoulder angles in either direction ($F_{3,16} < 1.99$, $p > 0.15$).

For all groups, trunk and shoulder angles tended to be aligned slightly with the visual scene when it was tilted to the ipsilesional/right side; however, the condition effect was not statistically significant ($F_{1,16} < 4.48$, $p > 0.050$). There was a significant group effect for both trunk and shoulder angles ($F_{3,16} > 4.48$, $p < 0.019$) for visual scene tilt to the ipsilesional/right side. HP ($F_{1,16} > 6.49$, $p < 0.022$)and NAP ($F_{1,16} > 7.57$, $p < 0.015$) trunk and shoulder angles were oriented less to the ipsilesional/right side than controls. There were no significant group ($F_{3,16} < 2.21$, $p > 0.12$) or condition effects ($F_{1,16} < 3.17$, $p > 0.094$) for trunk or shoulder angles for visual scene tilt to the contralesional/left side.

The AP participant's trunk was oriented upright for conditions where the motion base was upright. His shoulders tended to be oriented more to his ipsilesional side, particularly in the start position and V ipsilesional trial.

Motion base tilted

Figure 4 shows the results for trials where the motion base tilted; there were no significant group-by-condition interactions for trunk or shoulder angles in the ipsilesional/right ($F_{3,16} < 0.38$, $p > 0.77$) or contralesional/left directions ($F_{3,15} < 0.41$, $p > 0.75$).

For motion base tilt to the ipsilesional/right side, there was a significant condition effect for shoulder angle ($F_{1,16} = 8.65$, $p = 0.0096$) but not trunk angle ($F_{1,16} = 3.18$, $p = 0.093$). For all groups combined, shoulder angles were oriented more to the ipsilesional/right side for VM trials (mean: 8.6°, standard deviation: 5.3°) than M trials (mean: 1.3°, standard deviation: 5.9°). For motion base tilt to the ipsilesional/right side, there were significant group effects for trunk and shoulder angles ($F_{3,16} > 8.05$, $p < 0.0018$). Specifically, NAP trunk and shoulder angles were oriented more to the ipsilesional/right side than controls ($F_{1,16} > 6.18$, $p < 0.025$), whereas HP shoulder angles were oriented less to the ipsilesional side than controls ($F_{1,16} = 10.74$, $p = 0.0047$). There was no significant difference between HP and control trunk angles ($F_{1,16} = 0.47$, $p = 0.50$).

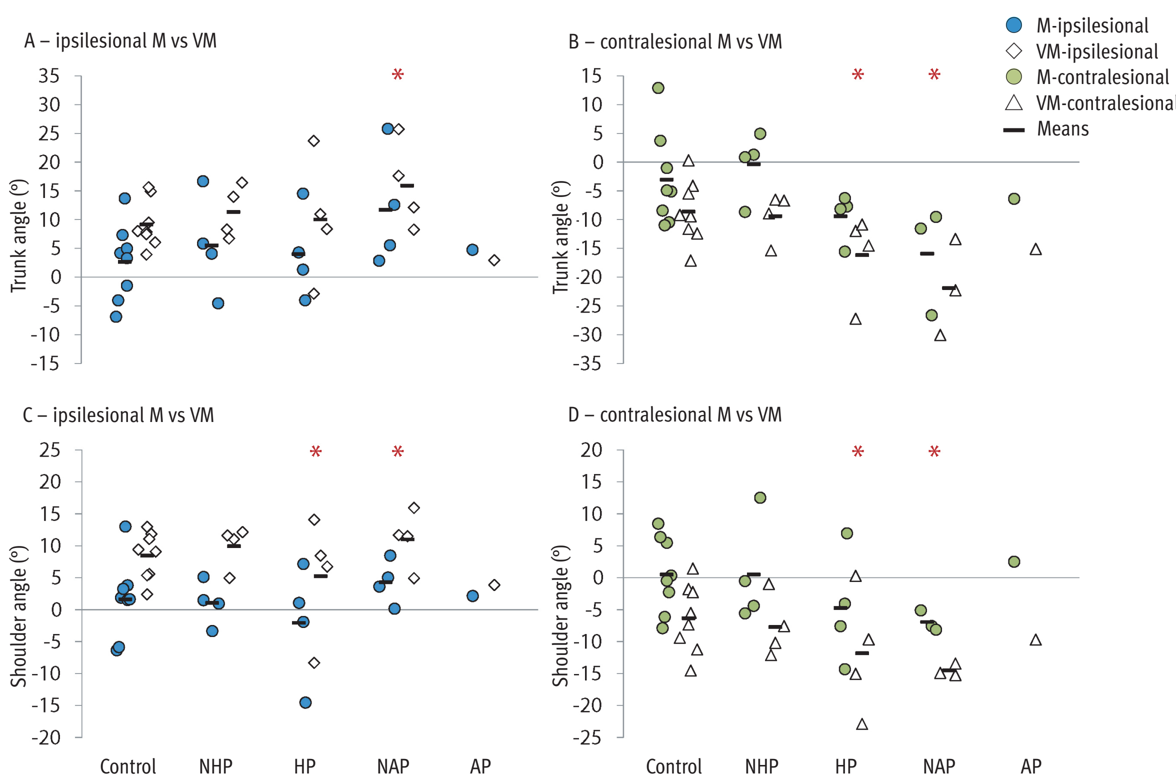

Fig. 4: Trunk and shoulder angles for trials where the motion base tilted. Panels A and B show trunk angles, and PanelsC and D shows shoulder angles. Values shown are data points for individual participants, with group means indicated by the black bars. Data points are 'jittered' along the x-axis to prevent overlap of points. Angles were calculated with respect to earth vertical/horizontal, with positive angles indicating orientation to the ipsilesional/right side, whereas negative angles indicate orientation to the contralesional/left side. The visual scene was aligned with gravity in the M trials and aligned with the motion base in the VM trials (see also Figure 2). Significant group effects are indicated with asterisks, where the groups significantly differed from the control group. There were no significant group-by-condition interaction effects for these conditions

There were significant condition effects for both trunk ($F_{1,15} = 5.20$, $p = 0.038$) and shoulder ($F_{1,15} = 6.24$, $p = 0.025$) angles for motion base tilt to the contralesional/left side. Trunk and shoulder angles were oriented more to the contralesional/left side for VM trials (trunk mean: -12.5°, standard deviation: 7.6°;shoulder mean: -9.1°, standard deviation: 6.4°) than for M trials (trunk mean: -5.9°, standard deviation: 8.6°; shoulder mean: -1.8°, standard deviation: 7.0°). For motion base tilt to the contralesional/left side, there were significant group effects for trunk and shoulder angles ($F_{3,15} > 16.40$, $p < 0.0001$). Specifically, both HP ($F_{1,15} > 19.47$, $p < 0.0006$) and NAP ($F_{1,15} > 36.23$, $p < 0.0001$) trunk and shoulder angles were oriented more to the contralesional/left side than controls.

The AP participant's shoulder and trunk angles in the M trials were similar to those of controls. In the VM ipsilesional trial his trunk was more closely aligned with earth vertical than controls, where as for the VM contralesional trial his trunk and shoulders were aligned to his contralesional side.

Discussion

This study aimed to determine how people with and without history of post-stroke pushing behaviour use visual and graviceptive cues to control seated postural orientation. Participants generally adjusted posture in an attempt to stay upright with respect to earth vertical following the motion base perturbation, in agreement with previous work [11].For M trials, where the motion base tilted with the visual scene upright, participants did not fully correct posture to earth vertical; this was likely due to limitations in spine range of motion that cannot fully compensate for this postural perturbation. The difference in trunk and shoulder angles between the VM and M conditions was approximately half of the difference in visual scene orientation between these conditions (~7°). Previous work suggests that perception of upright is approximately equally influenced by visual and graviceptive cues [7]. The current study extends these previous findings by suggesting that humans use visual and graviceptive cues approximately equally to re-orient to upright after a postural perturbation.

We did not find evidence that participants with stroke were more susceptible than controls to postural deviations from upright in the presence of conflicting visual cues. For most conditions, HP participants' posture was oriented more to the contralesional side than controls; despite resolution of obvious pushing behaviour, these individuals might still show sub-clinical signs of pushing that influence postural orientation [13, 14]. NAP participants also showed contralesional postural biases in the conditions where the motion base tilted to the contralesional side, and showed ipsilesional postural biases when the motion base tilted to the ipsilesional side. Orientation biases for NAP participants condition may reflect reduced trunk strength/control and, therefore, reduced capacity to correct postural orientation following these postural perturbations. It is possible that, due to delayed recovery for those with pushing behaviour [1, 5, 6, 17], HP participants' postures were also influenced by reduced trunk strength/control rather than perceptual impairment. Alternatively, it has been suggested that pushing behaviour occurs on a continuum rather than being strictly binary [18]. Thus, despite no clinical evidence of pushing behaviour, some NAP participants may have had sub-clinical pushing, which may account for the contralesional postural orientation for some participants.

The AP participant's postural orientation did not appear to be influenced by conflicting visual cues to upright, particularly when the motion base was upright. Our companion paper describes how this participant also did not appear to use visual cues to perceive upright [8]. In general, this participant's postural orientation followed a similar pattern to HP participants. Of note, when the motion base tilted to the ipsilesional side, the AP participant and most of the HP participants had very little ipsilesional bias, in contrast to the other groups. This postural orientation is consistent with the clinical presentation of pushing behaviour, and resistance to being passively moved to the ipsilesional side [16].

Summary

This study suggests that people with stroke with and without a history of pushing behaviour do not rely more on static visual cues to control postural orientation than people without stroke. Previous interventions focused on remediating pushing behaviour by asking participants to align their bodies with visual references to vertical (e.g., door frames) have not been as effective as interventions that stimulate somatosensation of earth vertical [2, 12]. The current findings may help to explain the results of these intervention studies.

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Conflict of interest:
The authors state that there is no conflict of interest.

Correspondence to:
Avril Mansfield
Room 11-117, 550 University Ave, Toronto, ON
M5G 2A2, tel: 416-597-3422 ext 7831
avril.mansfield@uhn.ca