Communication

Postural Control Disturbances Induced by Virtual Reality in Stroke Patients

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Abstract: People who survive a stroke are often left with long-term neurologic deficits that induce, among other impairments, balance disorders. While virtual reality (VR) is growing in popularity for postural control rehabilitation in post-stroke patients, studies on the effect of challenging virtual environments, simulating common daily situations on postural control in post-stroke patients, are scarce. This study is a first step to document the postural response of stroke patients to different challenging virtual environments. Five subacute stroke patients and fifteen age-matched healthy adults were included. All participants underwent posturographic tests in control conditions (open and closed eyes) and virtual environment without (one static condition) and with avatars (four dynamic conditions) using a head-mounted device for VR. In dynamic environments, we modulated the density of the virtual crowd (dense and light crowd) and the avoidance space with the avatars (near or far). Center of pressure velocity was collected by trial throughout randomized 30-s periods. Results showed that more challenging conditions (dynamic condition) induced greater postural disturbances in stroke patients than in healthy counterparts. Our study suggests that virtual reality environments should be adjusted in light of obtaining more or less challenging conditions.

Keywords: stroke; postural control; virtual reality; head-mounted display; optic flow; aging

1. Introduction

A stroke is a serious life-threatening medical condition characterized by the interruption of blood flow to a part of the central nervous system due to an ischemic or hemorrhagic vascular injury [1]. Patients who survive a stroke (SP) suffer from various somatosensory impairments, motor dysfunction, perceptual, visual disturbances, and altered spatial cognition with reference to the upright body position [2–4], resulting in balance disorders [2,3]. SPs show changes in motor strategies for postural control with delayed and reduced anticipatory postural adjustments [4] and a shift in sensory weighting, with an increased reliance on visual information [5]. Balance disorders are responsible for medical complications due to falls and are associated with the inability to perform activities of daily life [4].

Among the wide variety of motor rehabilitation programs, virtual reality (VR) has shown promising results as a means of improving postural control abilities [6,7]. VR is defined as "the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real-world objects and events" [8] and features immersive systems such as head-mounted

display [9]. Immersive VR using a head-mounted display seems to be safe and feasible in stroke patient rehabilitation [10]. VR technology offers the possibility to immerse people in a 3D environment that can mimic a real-life scenario, allowing assessment of postural control in more realistic situations with the possibility to manipulate, in a reproducible way, the task complexity [11].

Previous work indicates that static virtual environments (VE) do not appear to challenge postural control [12,13] whereas dynamic scenes induce postural perturbations in healthy young adults (HA) [12] and older adults [14]. However, D'Antonio et al. [15] reported lesser postural perturbations in SP and older HA compared with young HA in semi-immersive environment. To date, there exists no clear evidence on the effects of static and dynamic immersive VE on postural control in SP, specifically in ecological environments with irregular visual flows. Immersive VR, compared to semi-immersive or screen projection, improves the immersion and the presence (being in the virtual world) of the patients [16] and should be preferred in investigating the VR effect on postural control and in rehabilitation programs.

The current study aimed to investigate the effects of dynamic VE on the postural control in SP and HA. Dynamic VE consisted of visual flow modulation including a crowd of walking avatars. We hypothesized that stroke patients would show greater postural perturbations in dynamic VE than HA, given that they are strongly reliant to visual information to maintain postural control, with increased responses in more challenging VE.

2. Methods

Five age-matched SP (61.2 ± 7.05 years old, range: 51–69 years, two women) and 15 age-matched HA (59.1 ± 2.8 years old, range: 55–65 years, nine women) participated in the study conducted in the Physical Medicine and Rehabilitation department. The inclusion criteria were as follows: adults (>18 years old) with subacute paresis [14 days–6 months] having given informed agreement. The exclusion criteria were: (i) standing upright for less than 1 min without assistive device; (ii) cognitive impairment (Mini Mental State Examination < 24); (iii) inability to understand the instructions (Boston Diagnostic Aphasia Examination (BDAE) < 2); (iv) visual or auditory impairment; (v) motion sickness in VE by adverse events (e.g., vertigo); and (vi) neurological or orthopedic complications modifying quiet standing. All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University Hospital Center of Poitiers (CHU86-RECH-R2021-02-01).

A clinical assessment of fear of falling with the Falls Efficacy Scale-International (FES-I) and balance abilities with Postural Assessment Scale for Stroke Patients (PASS) was filled by the SP.

Before starting the postural control assessment, each participant discovered neutral VE in a seated position and carried out a 30-s familiarization trial on a force platform. Then, postural control assessment was performed while participants were positioned with bare feet oriented at 30° from the sagittal midline in two control conditions: open eyes (OE) and closed eyes (CE); and in two types of VE (Figure 1A): a static virtual environment where the participant is in the middle of a room without any avatars (Figure 1B), and dynamic virtual environments, which represent a commercial center with moving avatars walking at spontaneous velocity following random displacements ($1.1 \ m \cdot s^{-1}$) (Figure 1C–F). Dynamic virtual environments (DVEs) provided four visual conditions obtained by the modulation of virtual crowd density (sparse and dense) and avoidance space with avatars (wide: 0.8 m and narrow: 0.1 m). We thereby tested four DVE conditions: sparse and wide (SW); dense and wide (DW); sparse and narrow (SN); and dense and narrow (DN) (Figure 1C–F). Conditions were randomly assigned before the beginning of the session. After each condition, participants were asked to determine the difficulty in identifying feelings to maintain posture stability with a visual analogue scale (VAS) from 0 to 10 (0 no difficulty and 10 unable to perform).
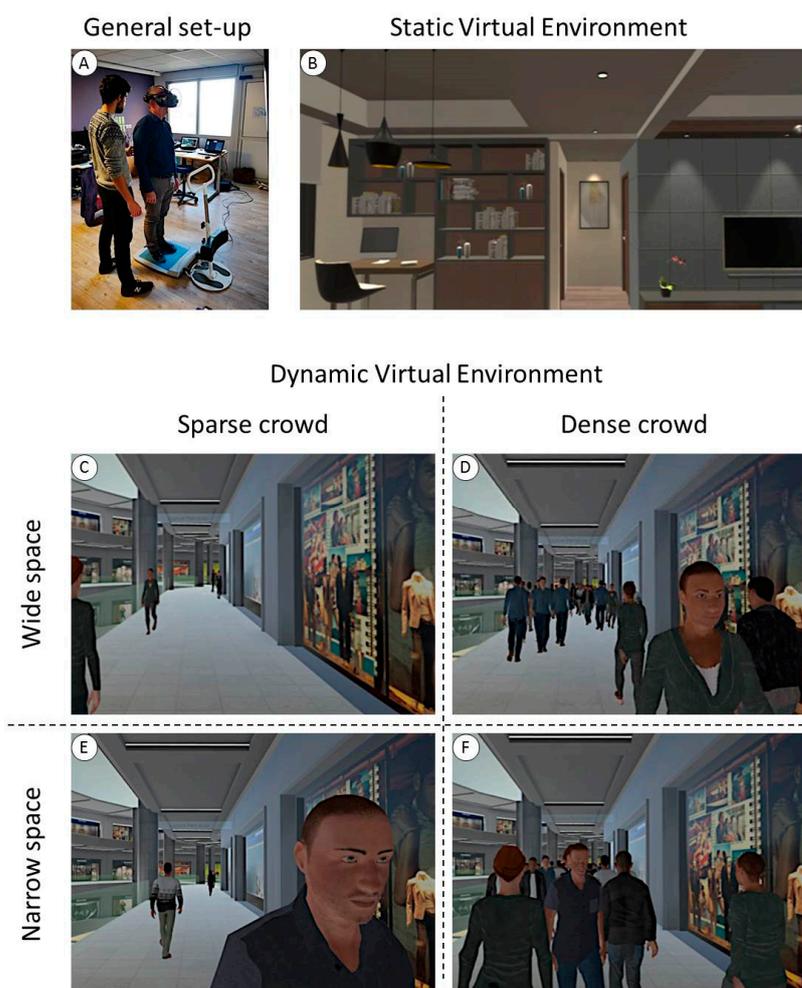
Figure 1. General experimental setup (**A**), static virtual environment (**B**), and dynamic virtual environment in sparse crowd and wide space (**C**), dense crowd and wide space (**D**), sparse crowd and narrow space (**E**), and dense crowd and narrow space (**F**) conditions.

During assessment, safety devices (i.e., human security, metal frame) were put in place to prevent falls (Figure 1A). Postural data were collected over 30 s per trial with a 1-min rest between trials. A WIN-POSTURO force platform (Medicapteurs®, Co. France) was used to measure the center of pressure (CoP) displacement (sampling rate: 40 Hz [17]), and an head-mounted display device (HTC® Vive, HTC Co., New Taipei City, China) with a large field of vision (110°) and a high resolution screen (1200×1080 px each eye) to display VE (Virtualis® software, Co. France). CoP velocity was expressed in mm·s^{-1} (corresponding to the cumulative distance over the sampling period) [18]. To investigate the effect of visual attention on postural control due to VE, we used the following equation: VRcost =(VE − OE)/OE∗100) (in%). Raw signals were imported in MATLAB (Mathworks Inc., Natick, MA, USA) and low-pass filtered (fourth order low-pass zero-phase lag Butterworth filter, 7 Hz cut-off frequency) prior to computing the CoP velocity.

The data are presented as median with data range. The Mann–Whitney U-test was performed to compare postural performance (i.e., CoP velocity and Vrcost) between the OA and HA groups. Statistical analysis was carried out with SPSS Statistics® 22 software (IBM Corp, Armonk, NY, USA) with a p-value < 0.05.

3. Results

Twenty-two SP and 15 HA were screened, where 17 SP were not included for the following reasons: six for wearing of an orthosis, six could not stand for one minute, two

for visual trouble, one for motion sickness, one for hip surgery, and one for cognitive impairment. As shown in Table 1, the socio-demographic variables of both groups were homogeneous. Clinical characteristics of SP were a Barthel index of 87 [70–100]; PASS of 33.6 [32–36]; and FES-I of 26.6 [16–39]. There were four left and one right superficial sylvian ischemic strokes and three of them had aphasia. SP had a NIHSS (National Institutes of Health Stroke Scale) of 6 [6–9] at admission into the department.

Table 1. Clinical data and postural control data.

Parameters	Stroke Patients	Healthy Adults	*p*-Value
Population (N)	5	15	-
Women (N (%))	2 (40)	9 (60)	0.479
Age (years)	61.2 ± 7.1	59.1 ± 2.8	0.334
BMI (Kg/cm^2)	25.9 ± 2.2	25.7 ± 3.9	1
Barthel	87.0 [70:100]	-	-
PASS	33.6 [32:36]	-	-
FES-I	26.6 [16:39]	-	-
NIHSS	6.0 [6:9]	-	-
CoP velocity (mm.s^{-1})			
Open Eyes	13.1 [11.0; 18.0]	11.8 [9.2; 14.0]	0.275
Closed Eyes	19.7 [18.8; 21.3]	17.6 [14.9; 22.0]	0.266
Static virtual environment	15.6 [13.6; 15.8]	10.7 [9.7; 12.9]	0.098
Dynamic virtual environment SW	15.1 [14.8; 15.9]	10.7 [9.7; 14.0]	0.025 *
Dynamic virtual environment DW	16.9 [15.8; 18.2]	12.2 [10.5; 14.7]	0.015 *
Dynamic virtual environment SN	16.0 [13.4; 18.9]	11.7 [8.7; 13.8]	0.025 *
Dynamic virtual environment DN	18.2 [18.1; 19.2]	13.0 [11.3; 17.2]	0.042 *
Vrcost (%)			
Static virtual environment	17.7	2.8	0.23
Dynamic virtual environment SW	28.8	4.5	0.197
Dynamic virtual environment DW	31.2	13.1	0.081
Dynamic virtual environment SN	38.1	2.9	0.081
Dynamic virtual environment DN	51.9	20.9	0.033 *
VAS (0–10)			
Open Eyes	2.0 ± 2.1	1.1 ± 1.2	0.479
Closed Eyes	3.2 ± 2.6	2.2 ± 1.9	0.403
Static virtual environment	2.3 ± 1.7	1.3 ± 1.7	0.215
Dynamic virtual environment SW	2.4 ± 2.1	1.2 ± 1.2	0.215
Dynamic virtual environment DW	2.6 ± 1.8	1.5 ± 1.6	0.25
Dynamic virtual environment SN	2.4 ± 2.1	1.3 ± 1.3	0.271
Dynamic virtual environment DN	3.5 ± 2.6	1.9 ± 1.7	0.202

Age and BMI (Body Mass Index): mean ± SD (standard deviation); CoP displacement velocity (mean velocity): Med [Q1; Q3]. D: dense; N: Narrow; S: sparse; W: Wide; PASS: Postural Assessment Scale for Stroke; FES-I: Fall Efficacy Scale—International; NIHSS: National Institutes of Health Stroke Scale; Vrcost: Virtual Reality cost (Vrcost = (VE − OE)/OE × 100). VAS: Visual Analogic Scale from 0 no difficulty to 10 unable to perform (mean ± SD); *: $p < 0.05$.

Postural control data are presented in Figure 2. There were no significant differences of CoP velocity displacement between SP and HA in open eyes ($p = 0.275$), closed eyes ($p = 0.266$), and static virtual environment ($p = 0.098$) conditions. In contrast, our results revealed that CoP velocity was greater in SP than HA for all dynamic virtual environment conditions ($p < 0.05$).
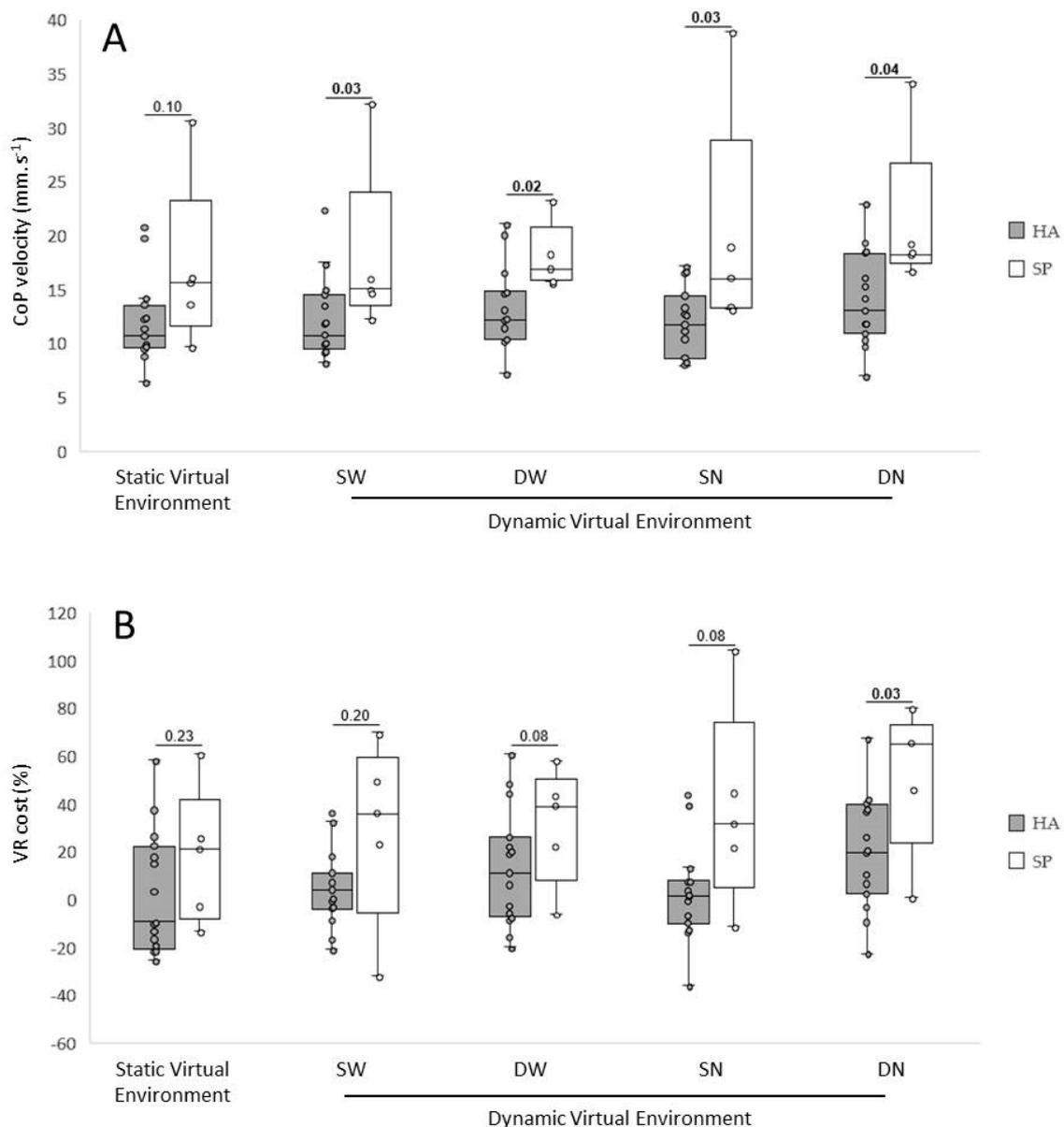
Figure 2. CoP velocity (**A**) and Vrcost (**B**) between HA (healthy adults) and SP (stroke patients). CoP: Center of Pressure; Vrcost: Virtual Reality cost; D: dense; N: Narrow; S: sparse; W: Wide.

Furthermore, the Vrcost appeared significantly higher for SP than HA in the dynamic virtual environment DN condition (51.9% for SP and 20.9% for HA, $p = 0.033$). Vrcost did not appear significantly different in any other conditions ($p > 0.05$). No group effect was observed for difficulty in identifying feelings (VAS) for all conditions.

4. Discussion

This study aimed to compare the impact of static and dynamic virtual environments (i.e., visual flow modulation including a crowd of walking avatars) on postural control in SP with HA. CoP velocity was significantly greater for SP than for HA in the dynamic virtual environment, and Vrcost was greater in SP than HA in the dynamic virtual environment of dense and narrow conditions, showing that the difficulty of VE more influenced the postural control in SP compared with HA.

While we found that the postural control of SP and HA was not differently altered in the SVE condition, it was more perturbed in SP than in HA under DVE conditions.

In a recent study, Chiarovano et al. [14] reported that the percentage of postural control deficit in a virtual environment increased with age and amplitude of the moving scene. In addition, it has been shown that postural control of SP is affected by visual rather than proprioceptive or vestibular perturbation [5]. Many authors have suggested that in comparison with young adults, older adults and SP are not able to adapt their postural behavior to the external perturbations [15,18,19]. In our study, challenging VE led to more pronounced postural perturbation in SP than in HA, which is consistent with their strong reliance on visual information [5]. Furthermore, in contrast to other studies evaluating the effect of VR on postural control [12,13,15], we proposed a multiple complex task with various optical flow induced by changing the density and avoidance space of avatars in a crowded environment. All in all, we suggest that immersive and various ecological virtual environment conditions can be used in SP virtual reality rehabilitation programs with progressive challenging situations.

In addition, it has been reported that attentional demand increases in SP compared to HA, especially when conditions become more challenging [20]. In a near-infrared spectrometry study, Hinderaker et al. [21] showed that attentional cost, illustrated by prefrontal cortex activation modulation, rose in older adults under challenging balance conditions. This process may be exacerbated in SP and could be partially related to postural control alteration in a challenging VR environment. VR permits a standardized and reproducible environment that can be used to present ecological situations [11] and can provide an additional assessment by observing SP behavior in daily living activities.

While the VR environment provided clear postural impairment in SP, our study was not free of limitations. While the sample size of SP was small, our study showed that among 22 SPs, only five met our inclusion criteria. This limited enrolment is related to the fact that screening was performed in routine practice and we chose to recruit patients with high postural capabilities (PASS: 33.6 [32:36]) to test a wide range of VR conditions. Regardless of these limitations, our pilot study provides new insights that should be considered in future randomized controlled trials. Furthermore, investigation of the underlying mechanisms of postural control alteration in VR for both SP and HA needs to be undertaken to improve the VR rehabilitation program.

5. Conclusions

Our study showed that dynamic VE had a greater impact on postural control in stroke patients than in healthy adults, all the more so when challenging ecological situations are presented (crowded environment). While immersive VR is currently used to improve postural control in stroke rehabilitation, our study suggests that the level of visual perturbation should be adjusted to provide more or less challenging conditions for postural control.

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