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Optic flow in a virtual environment can impact on locomotor steering post stroke

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Persons with a chronic stroke often manifest mobility deficits that may in part be related to altered visuomotor control. Specifically, the ability to use optic flow, which reflects self-motion, may be compromised after a stroke. We evaluated the locomotor behavior of 6 subjects with chronic stroke as they walked overground while viewing a virtual room displayed in a head-mounted display. The subjects were asked to walk straight in the virtual environment (VE). At 1.5m of forward walking, the room was slowly rotated up to 40° towards the paretic or non-paretic side, or remained centered (0°). In order to maintain a straight trajectory or a small net heading error in the VE, subjects could rotate their head, with or without modifying their walking trajectory. The responses of subjects were varied in terms of strategies and accuracy, leading to a wide range of net heading errors. in the VE. While there was no precise biomarker of excellent performance, the two individuals with the poorest performance had a history of visuospatial neglect.

walking, steering, vision, stroke, hemiparetic, gait, visual motion, neglect

I. Introduction

The vast majority of stroke survivors are left with residual mobility deficits, since only 18% of the stroke population have non-limiting community ambulation capacity [1]. Many experience difficulty in adapting their locomotor behaviour to the constraints of the environment. Apart from decreased walking speed [2], they also have difficulty in steering, such as such walking and turning [3, 4]. These functional limitations are mainly attributed to muscle weakness (e.g. [5, 6]), but they may also be due to altered visuomotor control.

Vision problems are frequently present subsequent to stroke and have been linked to poor postural control [7] and an increased risk of falling [8]. Subjects with stroke often present poor visual acuity and hemianopia [9]. Neglect, a spatial awareness disorder characterized by a failure to attend to one side of the environment that is opposite the side of the lesion, can also contribute to poor sensory-motor performance [10] and postural instability [11].

People after stroke also have difficulty coordinating movements, likely related to altered sensorimotor processing [12]. Recently, research has shown that individuals who had a stroke did not exhibit the characteristic sequential reorientation of eye and body segments while walking and turning, an adaptive behavior that is consistently seen in the healthy population [3]. It appears that stroke subjects may have difficulty establishing a gaze centered frame of reference, which would make it difficult to achieve a stable representation of the body in space [12]. Indeed, there is a large proportion of stroke patients who fall while making a head or body turn [13].

There have been few studies directed towards understanding how stroke affects the perception of visual self-motion or optic flow. Optic flow is a predictable pattern of movement at the eye and it is a powerful cue used for navigation and heading direction [14]. Given the mobility challenges faced by stroke survivors and their associated visual deficits, understanding and characterizing steering strategies in response to changes in the perception of visual self-motion is needed and may have great potential for locomotor rehabilitation. The advancement of virtual reality (VR) systems has enabled us to overcome the challenge of manipulating and controlling optic flow to explore the role of visually guided locomotion in clinical populations. Recent work from our laboratory has revealed that subjects with stroke have difficulty modulating their walking velocity and their heading when presented with translational optic flows of changing speeds [15] and directions [16]. However, the translational vs. rotational nature of the flow directly impacts on steering strategies [17] and changing direction while walking involves a strong rotation of the perceived visual environment caused by eye, head and body reorientation in the new travel direction. Therefore, the objective of this study was to investigate the ability to guide locomotor steering in a virtual environment in response optic flow cues.

II. Methods

A. Participants

A sample of six subjects with stroke was recruited from the Jewish Rehabilitation Hospital in Laval, Quebec (Table 1). Subjects included were those presenting with no major cognitive impairments (scoring ≥27 on the Mini-Mental Status Examination) and some residual motor impairments (scoring ≤6 on the Chedoke-McMaster Inventory on leg and foot). Subjects also had to be able to walk independently for 10 m. Assistive devices such as canes were allowed if the participants regularly used them. Absence of visuospatial neglect was confirmed using the line bisection and star cancelation tests.

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TABLE I. SUBJECT CHARACTERISTICS

Subject	Sex	Age (yrs)	Time since stroke (yrs)	Type of Stroke	Location	Gait Speed (m/s)	Chedoke Leg	Chedoke Foot	MMSE	History of Neglect
S1	M	57	0.48	Right Hemmoraghic	Thalamus	0.61	3	3	30	no
S2	M	41	3.69	Right Ischemic	MCA, basal ganglia	0.38	3	6	30	no
S3	M	42	3.15	Right Hemmoraghic	MCA, basal ganglia	0.65	5	5	30	yes
S4	F	43	15.34	Right Ischemic	MCA	0.85	3	5	29	yes
S5	M	64	6.73	Left Ischemic	Sylvian, lentiform nucleus	0.32	5	6	29	yes
S6	F	71	2.14	Left Ischemic	MCA	0.42	4	3	29	yes

B. *Experimental Set Up*

Subjects walked overground in an open space in the laboratory (12m x 8m) while wearing a head-mounted display (HMD; NVisor with 60° diagonal field of view and 1280 x 1084 pixels resolution). The scene presented was that of a room with the same virtual dimensions as the laboratory (Fig 1). Subjects were outfitted with 41 passive reflective markers and motions of the head and body were captured at 120 Hz with a 12 camera Vicon-512™ system. Three-dimensional (3D) movements of the head were tracked real-time via three markers placed on the HMD. The 3D head position data were transferred to a software (CAREN-3, Computer Assisted Rehabilitation Environments, MOTEK BV) controlling the virtual display and synchronizing head movements with the scene displayed in the HMD.

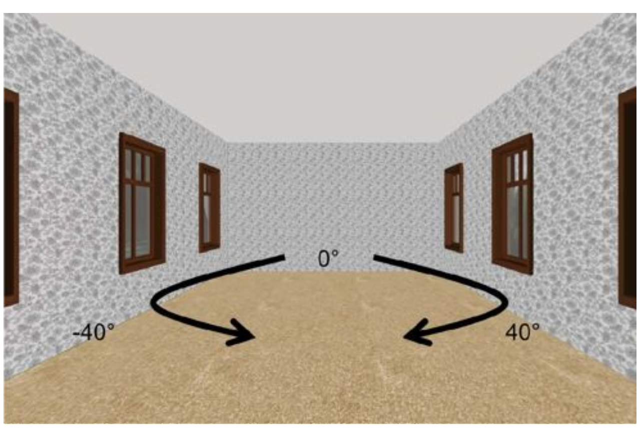

Figure 1. Image of scene viewed by participants in virtual environment. Arrows indicate rotation of visual scene in perturbation conditions

C. *Experimental Procedure*

Subjects were instructed to walk straight in the virtual room until a stop sign appeared at 5 meters of forward displacement. As they walked forward, they were exposed to one of three different optic flow conditions presenting three different focus of expansion (FOE) conditions: 1) FOE neutral, 2) FOE rotating towards the paretic side, or 3) FOE rotating towards the non-paretic side. In the neutral condition, the FOE was centered and movements of the VE directly corresponded to movements of the subjects in the physical laboratory. In the shifting FOE conditions, a visual perturbation was applied after 1.5 meters of forward walking. At this point, the scene started to gradually rotate either towards the paretic or non-paretic side (left or right), until reaching 40 degrees at 5 meters. This perturbation required that the participants either physically rotate their head or altered their walking trajectory in the opposite direction of the perturbation in order to maintain a perceived straight path in the virtual scene (Fig. 1). Subjects performed 5 trials in each condition for a total of 15 trials. Presentation of trials was block randomized.

D. *Variables Calculated*

Segmental angles in yaw were calculated for the head, trunk, pelvis and feet throughout the trial. Additionally, heading direction was calculated by determining the instantaneous angular deviations of the body's center of mass (CoM) trajectory in the horizontal plane, commencing from the onset of the FOE shift. As the scene viewed by participants could be adjusted by either rotating the head, or by altering the angular orientation of the CoM trajectory from origin point, a net heading correction variable combining 'head yaw' and 'heading' was calculated. Net heading errors, which reflected the participants' performance, was obtained as the difference between the net heading correction and the angular shift of the FOE at 5 meters of forward walking. Ideal performance would be reflected by a net heading error of 0 degree.

III. Results

As expected in a heterogeneous population such as stroke, subjects' behaviours vary considerably. Fig. 2 shows three different behaviours from three subjects. Subjects 1 and 6 exhibited 'expert' behaviour typically seen in healthy individuals, ie. walking straight in neutral FOE without significant deviations of the CoM and correcting in rotating FOE conditions by slightly reorienting their CoM in the direction away from the FOE shift. The largest of the net heading correction was achieved through head reorientation combined to small CoM trajectory heading changes (Fig. 3). As a result, perceived trajectory remained straight in the VE, with a net heading error that was very close to 0 degree (Fig. 2 top graphs, and Table 2).

Subject 2 displayed a large variability in their strategies in terms of the proportions of head and heading reorientation. They showed variable performances across trials with net heading errors ranging from 0 degree to 30 degrees, with a general tendency to undershoot (Fig 2 middle graphs, and Table 2).

Subjects 3, 4 and 5 showed marked inability to respond to changes in the flow presented. Their CoM trajectories were highly variable, consistent with many of the other subjects, but where they differed was in their head reorientation. They had much smaller or sometimes an absence of head reorientation. Their net heading errors were considerably higher when the FOE was shifted towards the paretic side (Fig. 2 bottom graphs, Table 2).

TABLE II. Percent error of performance at the end of the trial

Subject	FOE non-paretic	FOE paretic
1	2.4%	6.5%
2	33.8%	42.3%
3	51.0%	97.3%
4	62.0%	75.2%
5	17.5.1%	90.4%
6	7.5%	12.8%

IV. Discussion

The purpose of this study was to examine how subjects with stroke respond to changing optic flow directions in controlling their heading direction. VR provides a novel and precise method to investigate visuomotor control. In the past, optic flow research has relied on the use of prisms to manipulate visual cues during locomotion e.g. [18]. Those studies have been invaluable for investigating some of the control mechanisms of visually guided locomotion, yet they were also limited in the functional context of extrapolating to activities of daily living. When dealing with clinical populations, such as stroke, where the ultimate objective is

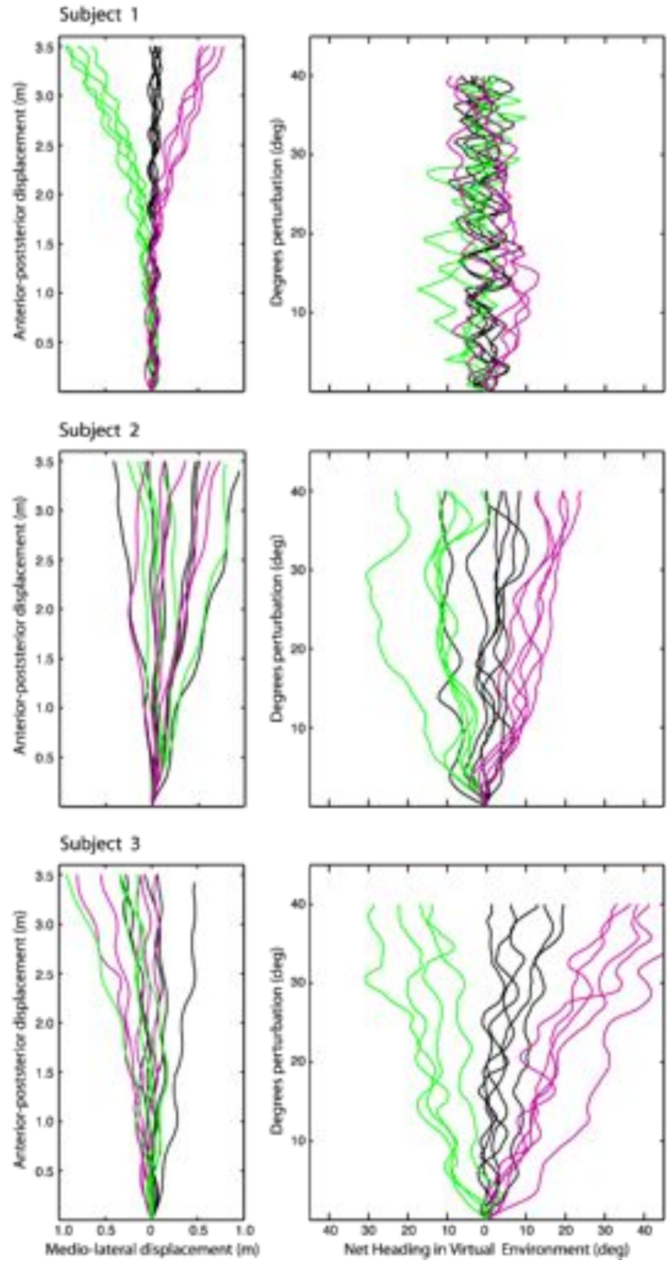

Figure 2. Trajectories of three subjects (S1, S2, S3) illustrating the 3 types of behaviours observed. Figures on the left show all the CoM trajectories for the subject. The figures on the right shows the corresponding Net Correction in the virtual environment. Trials in green represent cases where the FOE was shifting to the right (ipsilesional direction), trials in magenta the FOE is shifting left (contra-lesional), and there are no changes in the FOE for the black trials.

rehabilitation, it is important to consider the real world applicability of findings. Our study used a realistic scene to simulate a commonly encountered perturbation: rotations of the FOE. Every time an eye or head movement is made, the location on the FOE is rotated. The mover must correctly interpret this self-induced perturbation in order to maintain proper locomotor control. By simulating this in the laboratory, we were able to gain an insight into the variety of stroke behaviours related to visuomotor control.

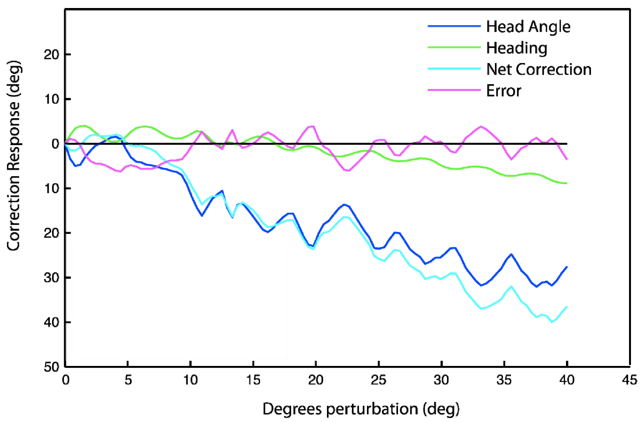

Figure 3. Reorientation strategies demonstrated by a stroke subject (S1) with expert performances induced by optic flow

Our expert subject S1 showed no stroke-related deficits to visuomotor control. This finding is very interesting because S1 had clear mobility issues and had difficulty walking for prolonged periods of time. Subjects that can properly interpret virtual visual information may benefit from therapies that use visually presented VEs to create realistic and ecologically relevant settings to practice and train locomotion in a progressive, motivating, and safe manner. Other investigators have also shown potentials for such use in virtual rehabilitation (e.g [19, 20]). Our work here suggests that manipulation of optic flows may be a useful therapeutic strategy to train complex locomotor tasks.

Other individuals with stroke (such as subject S2) appear to have inconsistent steering strategies leading to variable and moderately altered heading performances. Such behaviour may be due to an altered ability to regulate multi-sensory information. Indeed, the task presented involved the reconciliation of incongruent sensory information which may be difficult for some people after stroke [21]. Furthermore, as it has been shown that people with stroke have altered coordination of gaze, posture, and locomotion [3, 16], which may have contributed to enhance the variability in the strategies and performances of the subjects.

Finally, three of the subjects tested had profoundly altered responses to optic flows presented, despite otherwise presenting similar a functional level and similar types of lesions as other participants. Upon closer examination of the history of these three subjects, we found that they all had a history of visual spatial neglect. Even though the subjects passed the clinical examination of line-bisection test and the bell's test, their performance suggests on-going deficits in visual motion perception. Others have reported that those with neglect have difficulty maintaining walking trajectories, with a tendency to veer towards the ipsilesional side [22]. Our findings add to previous findings, suggesting that veering to the ipsilesional or non-paretic side may be due to an altered processing and/or perception of dynamic visual information, i.e. visual self-motion. Those deficits could remain long after clinical neglect, as assessed by paper-pencil tests, have resolved.

This preliminary work highlights the importance of ongoing research into how stroke impacts the ability to use visual motion information, which is critical to guide locomotion. The presence of a residual and adequate response in some of the participants suggest that virtual reality-based paradigms that manipulate visual motion information could be used to enhance mobility after stroke. It is clear that not all subjects have similar responses, yet the precise indicators or biomarkers for performance are to be determined. Early clinical signs of neglect may be a good indicator of those who will present with mobility problems characterized by steering difficulties.

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