Abstract— Gait asymmetry, one of the hallmarks of post stroke locomotion, often persists despite gait rehabilitation interventions, impacting negatively on functional mobility. Real-time feedback and biological cues have been studied extensively in recent years, but their applicability to post-stroke gait symmetry remain questionable. This proof-of-concept study examined the feasibility and instantaneous effects of real-time visual feedback provided in the form of an avatar in twelve participants with stroke on gait symmetry and other gait-related outcomes. The visual avatar was presented via three different views from the back, front and paretic side. Avatar feedback from the paretic side view showed significant increase in bilateral step length, paretic swing time ratio and treadmill walking speed, but no significant differences were found in symmetry measures in any of the three views. Those who had changes in symmetry ratio>0 were grouped as responders to spatial symmetry improvement in the side view. The responders had a significantly higher Chedoke-McMaster Stroke Assessment foot score and presented with a larger initial step length on the paretic side. Furthermore, all participants provided positive feedback and no adverse effects were observed during the experiment. Overall, these findings suggest that real-time avatar-based feedback can be used as an intervention to improve post-stroke gait asymmetry.

Index Terms— Gait asymmetry, avatar, cerebral vascular accident, virtual reality, real-time feedback

I. INTRODUCTION

STROKE is one of the leading causes of death and disabilities worldwide. Among all the impairments and limitations in activities of daily living caused by stroke, gait dysfunction is the most reported, and improving gait is the most important goal for the majority of people with stroke [1]. Immediately after stroke, more than half of the patients are not able to walk at all [2], and among those who can walk, their gait has many characteristics that differ from the gait of healthy individuals. Post-stroke gait not only features slow walking speed [3-5] but it is also characterized by deviations in kinematic/kinetic [6-8] and spatiotemporal parameters. Spatiotemporal deviations consist of decreased cadence [9, 10], shorter stride length [9, 10], increased time spent in double limb support [9], and wider base of support [10] compared to healthy gait. Walking after stroke is also portrayed by a number of inter-limb differences including prolonged swing phase on the paretic side and prolonged stance phase on the non-paretic side, which is commonly referred to as temporal asymmetry [11]. Spatially, some people with stroke exhibit a longer paretic step length while others exhibit longer non-paretic step length [12, 13]. These temporal and spatial asymmetries are commonly referred as gait asymmetry.

Gait asymmetry can lead to many negative consequences, including poor balance control [14], gait inefficiencies [15], increased risk of musculoskeletal injury to the non-paretic limb [16] and decreased overall physical function [17]. A longitudinal study on the changes in gait asymmetry over the course of inpatient rehabilitation indicated that even though the therapists were aware of the presence and magnitude of the gait asymmetry among their stroke clients, these clients did not significantly improve their gait asymmetry at discharge [18]. It was suggested that there was a lack of specificity of the gait interventions on gait asymmetry in the rehabilitation setting [18].

The development of contemporary interventions, including those targeting locomotor impairments post-stroke, rely on principles of motor learning and motor control [19]. Feedback is known to be one of the most important factors that contribute to skill acquisition and motor learning [20]. Feedback can be categorized either as terminal or concurrent feedback based on the timing at which it is delivered [21]. Concurrent feedback is defined as a feedback given “during task performance” while terminal feedback is given “at the completion of a motor task” [21]. The main advantage of concurrent feedback would be to guide the learners in order to feel the desired movement pattern and activation of certain musculature, so that ultimately the learners could improve their gait.
their movement pattern in the subsequent trials [21]. Real-time feedback is an example of concurrent feedback which was only recently explored in gait training research. It consists of providing instantaneous information about almost every aspect of gait of the subjects [22, 23]. One systematic review examined the effectiveness of real-time kinematic, spatio-temporal, and kinetic biofeedback in gait training among stroke survivors [24]. We concluded that real-time feedback resulted in greater short-term improvement to biomechanical parameters (e.g. narrower base of support, and faster walking speed than conventional therapy, while the retention effects were unclear. Furthermore, the immediate and retention effects of real-time feedback on outcomes of gait symmetry after stroke remain to be examined.

Feedback in the form of biological cues (i.e. cues that arise from live beings or animate objects) is a recent topic of interest in motor learning research [23], and it can be used to create human-like moving figures. An imaging study showed that the posterior superior temporal sulcus plays a special role in integrating information arising from human movement [25]. In fact, people are remarkably adept at recognizing the biological motion of a live being by looking at it, even when the kinematic patterns of the movements are portrayed by nothing more than a handful of light points attached to the head and major joints of the body [26, 27]. Furthermore, people are also adept at judging the direction in which animate objects are moving [28-31] and can also detect slight differences in the speed of animate objects [29]. Therefore, feedback in the form of biological cues could be used as a means to provide additional and more easily decipherable information about one’s spatiotemporal aspects of movement compared to conventional feedback delivered in the forms of verbal explanations, numbers and bar graphs. Recently, virtual avatars were used as a novel approach to investigate the influence of external visual biological cueing and/or feedback on locomotion and stepping movement [32, 33]. It is believed that virtual avatars could also elicit ‘gait synchronization,’ a phenomenon characterized by unintentional walking speed modifications and phase locking of rhythmic movements between two individuals walking side-by-side [34-37]. Studies which explored the use of avatars on post-stroke locomotion, however, were restricted to stepping activities [33] and/or had a very short exposure to the avatar (3s) [32], hence providing no information on short- and longer-term walking adaptations. Additional limitations included the use of a fixed-speed treadmill that hindered speed adaptations [32].

In the present study, we are proposing for the first time to explore the use of visual feedback in the form of virtual avatars (biological cues) displaying locomotion in real time to improve the symmetry of gait spatiotemporal parameters in people with stroke. In this proof-of-concept study that involved a single-time exposure to avatar-based feedback, we hypothesized that: (1) real-time visual feedback provided by avatars is a feasible and acceptable approach to improve gait symmetry and other parameters of gait in people with stroke; (2) the paretic side view provides the largest improvement in gait symmetry when compared to the frontal and back view of avatar because the side view has been shown to elicit fastest movement recognition [38]; (3) participants with higher gait capacity, and better motor recovery are more likely to improve the symmetry of spatiotemporal parameters with the avatar-based feedback because studies of post-stroke gait recovery suggested that people with faster gait speed, higher level of balance and motor recovery generally showed higher potential for recovery [18, 39]. Thus, the relationship between the level of initial gait asymmetry and the improvement in gait symmetry should also be examined.

II. METHODS

A. Experimental Design

A cross-sectional within-subjects design with repeated measures was used for this study.

B. Participants

Participants were included in this study if they met the following inclusion criteria: (1) having a first time sub-acute or chronic stroke (>6 months) supratentorial stroke; (2) age between 45 to 79 years; (3) being able to walk for 2 minutes independently while supervised, with or without a walking aid; (4) having a deficit in motor recovery of the lower limb, as indicated by stage scores ranging from 2 to 6 on the leg and foot components of the Chedoke-McMaster Stroke Assessment (CMSA); (5) having either temporal asymmetry (swing time ratio >1.06) or spatial asymmetry (step length ratio >1.08) [40] or both. Participants were excluded if they had (1) a stroke affecting brainstem or cerebellum; (2) co-morbid conditions such as cardiovascular, respiratory, musculoskeletal or other neurological conditions affecting locomotion; (3) dementia or cognitive deficits as indicated by scores < 24 on the Montreal Cognitive Assessment (MoCA); (4) severe aphasia or apraxia based on medical charts and initial screening; (5) non-corrected visual deficits; (6) a history of motion sickness or perceived handicap caused by dizziness, as indicated by a score > 16 on the Dizziness Handicap Inventory (DHI).

Participants were recruited from the Jewish Rehabilitation Hospital located in Laval, Quebec, Canada, which is a McGill University-affiliated teaching hospital and a research site of the Montreal Centre for Interdisciplinary Research in Rehabilitation (CRIR). This study received ethics approval from the Research Ethics Board of CRIR and all participants understood and signed the consent form prior to the first session of experiment.

C. Experimental Setup and Procedure

The data collection consisted of two sessions. The first session included habituating participants to a self-paced treadmill (described below) and evaluating them with the 10-Meter Walk Test, CMSA, MoCA and DHI in order to determine their overground comfortable speed, stroke severity, presence of cognitive deficits and history of motion sickness, respectively. These tests have demonstrated excellent psychometric properties [41-44].

In the second session, the participants performed the walking task on a custom-built self-pace treadmill (0.6 m x 1.5 m). The motor of the treadmill is driven by PID servo-control based on
the real-time distance and velocity feedback obtained with a potentiometer tethered to the participant [45]. A safety harness system suspended overhead was used to prevent the participants from falling. The treadmill is fitted with sliding handrails to assist with balance. The use of handrails, if applicable, was determined during habituation and was kept constant throughout the experiment. The participants who needed to use the handrail were instructed to only use it for balance, and not to put body weight on it during the habituation and the experiment. A screen (2.44 m × 3.05 m) was mounted in front of the treadmill for rear-projection of the virtual environment representing a long street with an avatar located 3.5 m ahead of the participant. Maya LT™ 2016 (Autodesk, USA) was used to design avatars of similar appearance and anthropometric characteristics to those of the participants. During the experiment, real-time tracking of the limb movement was provided by Tracker™ (Vicon, UK) based on the displacement of the 15 rigid bodies markers placed on the participant on specific body landmarks specified in Vicon Tracker™, which were tracked by the 6-camera Vicon™ (Vicon, UK) motion capture system. Pegasus Advanced™ (Vicon, UK) was used to retarget the limb positions onto a virtual avatar which would then be displayed on the screen and controlled using Unreal Engine 4 (Epic Games, USA). Kinematic data of participants were collected at 120 Hz in Vicon Tracker.

The participant performed two walking trials of each of the following conditions in a random order (Fig 1): (1) avatar viewed from the back; (2) avatar displayed with a paretic side view and; (3) avatar facing the participant. The paretic side was chosen because most gait deviations happened on the paretic side, and a clearer view of their gait deviations was preferred. The duration and number of trials were determined based on a previous study performed in healthy participants [46], while taking into account the limited endurance of stroke participants. Each trial had three phases which included 30s of comfortable walking without the avatar (pre-adaptation phase), followed by 1 min of walking while visualizing the avatar replicating the exact walking pattern of the participant in real time (adaptation phase), and finally 1 min of walking without the avatar (post-adaptation phase). Prior to the start of each trial, the following verbatim was given to participants: “Please wait for the "Go" sign on the screen before starting walking. When the trial starts, always walk with your comfortable speed and keep looking at the screen. For the first 30 secs, you will be looking at an empty street, then an avatar will appear. He (she) will mimic your way of walking in real-time, so please look at his (her) legs and feet for feedback and pay attention to your walking symmetry in at the same time. The avatar will disappear after 1 min, and you will be looking into the empty street again. Keep walking until you see the "Stop" sign.”. Participants were allowed to rest by sitting between the walking trials.

D. Data Analysis

Kinematic data were processed and exported using Vicon Nexus™ 1.8.5, before being analyzed in Matlab R2017b. To avoid the effects of acceleration and deceleration, data in the first and last 10 seconds of each trial were excluded. Data were normalized to 100% of the gait cycle, then filtered with a 4th order Butterworth low-pass filter at a cut-off frequency of 10 Hz.

The primary outcomes were step length ratio and swing time ratio, respectively, for the spatial and temporal components of gait symmetry. These two outcomes were calculated in the following way: first, rigid body markers were placed on the dorsum of feet along with additional reflective markers being put on the big toes and heels. This allows us to measure the distance between toe/heel and the rigid body markers. The reflective markers were then removed prior to the start of walking trials because they could interfere with the capturing of the movement of rigid body markers. The position data of rigid body markers plus the pre-determined distance between toes and heels were used for the calculation of swing time and step length. The ratios were calculated using the values of left and right side with the larger value in the numerator regardless of which side was the paretic [40]. A resulting value of ‘1.0’ indicated perfect symmetry.

Secondary outcomes included paretic and non-paretic step length and swing time and treadmill walking speed. The feasibility was evaluated using in-trial observations on whether a participant was able to complete all trials, whether there was pain or fatigue involved while performing the walking task, whether the handrail was used and if loss of balance/fall occurred. The acceptability was examined with a short interview post-experiment composed of the following questions: 1) overall, how do you like this avatar intervention? 2) do you feel that this avatar intervention changes the way you walk? 3) would you like to see this type of avatar intervention be implemented in the rehabilitation program in the future? 4) do you have a preferred view of the avatar (e.g. front, back or side)?

E. Statistical Analysis

Gait outcomes were averaged for each of the three phases (pre-adaptation, adaptation), separately for each avatar view. As for the primary outcomes of spatial and temporal symmetry, only data from participants who were considered ‘asymmetric’ were included for analysis. Since the data could not be assumed to follow a normal distribution, Friedman test was used to assess differences in gait symmetry and other outcomes across phases (pre-adaptation, adaptation, post-adaptation) for each
TABLE I
SUMMARY OF THE DEMOGRAPHIC AND CLINICAL RESULTS OF THE PARTICIPANTS

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Gender (Male/Female)</th>
<th>Age (years)</th>
<th>Stroke Chronicity (months)</th>
<th>Type of stroke (Ischemic/Hemorrhagic)</th>
<th>Stroke Location</th>
<th>Orthotics</th>
<th>Types of Asymmetry (Temporal: T/N; Spatial: Snp/Sn/S)</th>
<th>Comfortable Overground Walking Speed (m/s)</th>
<th>CMSA Score</th>
<th>Initial step length ratio</th>
<th>Initial swing time ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Female</td>
<td>51</td>
<td>324</td>
<td>Ischemic</td>
<td>L MCA+ frontal</td>
<td>None</td>
<td>T, Snp</td>
<td>0.79</td>
<td>5.2</td>
<td>1.08</td>
<td>1.23</td>
</tr>
<tr>
<td>S2</td>
<td>Male</td>
<td>67</td>
<td>12</td>
<td>Ischemic</td>
<td>L Ic</td>
<td>R AFO</td>
<td>T, Sp</td>
<td>0.80</td>
<td>5.3</td>
<td>1.12</td>
<td>1.07</td>
</tr>
<tr>
<td>S3</td>
<td>Male</td>
<td>66</td>
<td>25</td>
<td>Hemorrhagic</td>
<td>R Ic</td>
<td>None</td>
<td>T, Ts</td>
<td>1.02</td>
<td>5.5</td>
<td>1.03*</td>
<td>1.16</td>
</tr>
<tr>
<td>S4</td>
<td>Male</td>
<td>66</td>
<td>22</td>
<td>Ischemic</td>
<td>R lacunar</td>
<td>None</td>
<td>T, Snp</td>
<td>0.34</td>
<td>6.2</td>
<td>1.20</td>
<td>1.27</td>
</tr>
<tr>
<td>S5</td>
<td>Male</td>
<td>57</td>
<td>6</td>
<td>Ischemic</td>
<td>R Ic+Bg</td>
<td>None</td>
<td>Nt, Snp</td>
<td>1.10</td>
<td>5.4</td>
<td>1.14</td>
<td>1.02*</td>
</tr>
<tr>
<td>S6</td>
<td>Female</td>
<td>56</td>
<td>12</td>
<td>Ischemic</td>
<td>R MCA</td>
<td>None</td>
<td>T, Snp</td>
<td>0.89</td>
<td>4.4</td>
<td>1.08</td>
<td>1.12</td>
</tr>
<tr>
<td>S7</td>
<td>Male</td>
<td>77</td>
<td>40</td>
<td>Ischemic</td>
<td>L thalamus</td>
<td>None</td>
<td>T, Snp</td>
<td>0.29</td>
<td>4.5</td>
<td>1.26</td>
<td>1.22</td>
</tr>
<tr>
<td>S8</td>
<td>Male</td>
<td>58</td>
<td>33</td>
<td>Ischemic</td>
<td>R MCA</td>
<td>None</td>
<td>Nt, Snp</td>
<td>1.06</td>
<td>6.5</td>
<td>1.09</td>
<td>1.03*</td>
</tr>
<tr>
<td>S9</td>
<td>Male</td>
<td>49</td>
<td>52</td>
<td>Ischemic</td>
<td>R Sylvian</td>
<td>L AFO</td>
<td>T, Snp</td>
<td>0.74</td>
<td>5.4</td>
<td>1.77</td>
<td>1.10</td>
</tr>
<tr>
<td>S10</td>
<td>Male</td>
<td>65</td>
<td>165</td>
<td>Ischemic</td>
<td>R Sylvian</td>
<td>None</td>
<td>T, Sp</td>
<td>0.35</td>
<td>3.2</td>
<td>1.04*</td>
<td>1.24</td>
</tr>
<tr>
<td>S11</td>
<td>Female</td>
<td>58</td>
<td>26</td>
<td>Ischemic</td>
<td>R thalamus</td>
<td>None</td>
<td>T, Snp</td>
<td>0.86</td>
<td>4.4</td>
<td>1.08</td>
<td>1.08</td>
</tr>
<tr>
<td>S12</td>
<td>Male</td>
<td>56</td>
<td>72</td>
<td>Ischemic</td>
<td>R Bg</td>
<td>L AFO</td>
<td>T, Snp</td>
<td>0.86</td>
<td>4.3</td>
<td>1.02*</td>
<td>1.09</td>
</tr>
</tbody>
</table>

SD: standard deviation; CV: coefficient of variation; L: left; R: right; MCA: middle cerebral artery; Ic: internal capsule; Bg: basal ganglia; AFO: ankle-foot orthosis; T: temporal asymmetry; Nt: no temporal asymmetry; Snp: spatial asymmetry with non-paretic side larger; Sn: spatial asymmetry with paretic side larger; Ns: no spatial asymmetry; CMSA: Chedoke-McMaster Stroke Assessment; MoCA: Montreal Cognitive Assessment; DHI: Dizziness Handicap Inventory. *These values were not considered to be asymmetrical.

avatar view separately. Wilcoxon signed-rank test was then used to conduct post-hoc pairwise analysis between phases, with Bonferroni-Holm correction adjustments. To calculate the effect size, the formula proposed by Rosenthal (1994) \( r = \frac{z}{\sqrt{N}} \) was used [47]. If \( r \) was between 0.1 and 0.3, the effect size was considered small; between 0.3 and 0.5, it was medium and above 0.5, it was large [48].

Responders vs. non-responders to the avatar-based feedback during adaptation phase were further compared on their overground comfortable walking speed, CMSA leg and foot scores, initial step length ratio using Mann-Whitney U tests. In the context of this study, responders were defined as participants showing an improvement in symmetry (ratio change > 0) and were considered separately for spatial and temporal symmetry. Since people with stroke can present with one of two directions of step length asymmetry, i.e. a longer paretic step length or a longer non-paretic step length [12, 13], the directions of step length asymmetry was also examined as an explanatory variable for responders vs. non-responders. The statistical analyses were performed in SPSS v.24 (IBM Inc, USA), and the significance level needed to reject the null hypothesis was set at \( p \leq 0.05 \).

III. RESULTS

Twelve participants with stroke were recruited after the clinical screening process in the period between December 2017 and February 2019. Table 1 outlines the demographic and clinical results for all participants. The participants consisted predominantly of people who are males (ratio: 9:3), affected on right hemisphere (ratio: 9:3), and who had an ischemic stroke (ratio: 10:2). Also, 3/12 participants wore ankle-foot orthosis; T: temporal asymmetry; Nt: no temporal asymmetry; Snp: spatial asymmetry with non-paretic side larger; Sn: spatial asymmetry with paretic side larger; Ns: no spatial asymmetry; CMSA: Chedoke-McMaster Stroke Assessment; MoCA: Montreal Cognitive Assessment; DHI: Dizziness Handicap Inventory. *These values were not considered to be asymmetrical.
asymmetrical), hip hiking (2/10), and hip circumduction (2/10). Furthermore, 10/12 participants also reported that they felt more confident in walking with this avatar-based training. In addition, they all believed that this type of intervention would have the potential to be implemented in a stroke rehabilitation program and that it could be beneficial for other people with stroke. Finally, when asked which view they preferred the most, 5/12 reported preferring the side view, 4/12 the back view and 3/12 the frontal view.

B. Symmetry of Spatiotemporal Parameters

When considering the group results, neither swing time ratio (n=10) nor step length ratio (n=9) showed statistically significant differences across the three phases for all three views (Fig 2A right and left). From pre-adaptation to adaptation, however, a trend for increased swing time ratio (worsened symmetry) was observed for all three views while step length ratio tended to improve in the side view only. A large inter-subject variability that was reflected by large standard deviations were also observed in terms of the participants’ outcomes across phases, especially for step length ratios in the adaptation phase to the side view. Given these observations, an analysis of individual results was performed for the side view specifically and the results are presented in the next section on responders vs. non-responders.

Analysis of group results also revealed that for the side view only, both the paretic ($\chi^2=9.23$, $p=0.01$) and non-paretic step lengths ($\chi^2=15.17$, $p \leq 0.001$) varied across walking phases.
**Step length ratio in side view (paretic STL larger)**

![Graph showing step length ratio in side view with paretic STL larger](image)

**Step length ratio in side view (non-paretic STL larger)**

![Graph showing step length ratio in side view with non-paretic STL larger](image)

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**Fig. 3.** Step length ratios of each participant across 3 phases in the side view condition, STL: step length. Black represents a larger non-paretic step length while grey a larger paretic step length. The solid lines indicate responders and the dash lines non-responders.

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**Fig. 4.** Difference of step length ratio between the adaptation phase and pre-adaptation phase for participants with a larger paretic and non-paretic sides. A negative value of the difference in step length ratio is improvement while a positive value is deterioration. Means and standard deviations are shown by the bars and whiskers. Statistically significant differences are indicated by * (p ≤ 0.05).

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(Figure 2B). For the paretic step length, post-hoc analyses revealed a significant increase between adaptation and pre-adaptation (0.020±0.022 m, CV: 110%; Z=2.432, p = 0.015) but no significant difference between post-adaptation and pre-adaptation (Z=1.337, p =0.181). On the non-paretic side, step length was found to be larger in the adaptation vs. pre-adaptation (0.033±0.020 m, CV: 61%; Z=3.061, p = 0.002) and post-adaptation vs. pre-adaptation phase (0.034±0.038 m, CV: 112%; Z=2.510, p = 0.012). A significant effect of walking phase was also observed for swing time on the paretic side only in the side view (χ²=6.83, p ≤0.033), due to a larger swing time in adaptation vs. pre-adaptation (0.012±0.014 s, CV: 117%; Z=2.847, p =0.004). Treadmill walking speed (Figure 2C) was also found to significantly differ across walking phases for the side view only (χ²=9.44, p =0.009). The post-hoc analyses revealed faster treadmill speeds between adaptation vs. pre-adaptation (0.062±0.059 m/s, CV: 95%; Z=2.667, p =0.008), as well as between post-adaptation vs. pre-adaptation (0.072±0.083 m/s, CV: 115%; Z=2.276, p=0.023). Large effect sizes with r values ranging from 0.66 to 0.88 were observed with all the statistically significant results.

**C. Responders vs Non-responders of step length ratio to the side view**

As illustrated in Fig. 3, three out of four participants who initially had a larger paretic step length improved their step length ratio during the adaptation phase, and one participant did not change. In contrast, all participants with a larger non-paretic step length saw a deterioration in step length symmetry. When comparing the group mean values (those with larger paretic vs. non-paretic step length), the differences in step length ratio between adaptation and pre-adaptation were respectively -0.06 ±0.05 vs. 0.04±0.02, and this was found to be significant (Z=-2.46, p =0.014) (Fig. 4). Furthermore, when comparing post-adaptation to pre-adaptation, three out of four participants who had a larger paretic step length improved their step length ratio (same participants who also improved during adaptation) while one deteriorated. Two out of five participants who had a larger non-paretic step length improved their step length ratio while three deteriorated. The group mean values, were respectively -0.05 ±0.06 vs. 0.02±0.03 for those with a larger paretic and non-paretic step length, but it was found to be non-significant (Z=-1.85, p=0.063). Responders, i.e. those who improved their step length symmetry in response to the side view during adaptation, also had significantly larger CMSA foot score compared to non-responders (4±0.58 vs 3±0.89, Z=-2.04, p =0.041). They presented, however, similar overground comfortable walking speed (Z=-0.78, p =0.439), CMSA leg scores (Z=-0.28, p =0.783) and initial step length ratio (Z=-1.58, p =0.115).

**IV. DISCUSSION**

This study examined for the first time the effects of visual feedback in the form of virtual avatars displaying locomotor movements in real time on gait symmetry and other parameters of gait among people with stroke. This study was also the first to compare the effects of back, front and side views of avatar on gait symmetry. Although no significant changes were seen in the primary outcomes (swing time ratio and step length ratio) in any view condition, the side view provided the most interesting changes on secondary outcomes across participants. These changes and possible mechanisms are discussed below.
A. A Feasible Modality with Benefits on Self-Efficacy

It was shown in this study that real-time visual feedback in the form of virtual avatars was well tolerated by all participants and did not cause any discomfort. Furthermore, the results of acceptability showed that most participants felt more confident during the exposure of avatars compared to their everyday walking and were able to enjoy walking more with the training. In fact, people with stroke are often associated with low self-efficacy and perceived disability in physical activities [49, 50].

It is stated in the literature that self-efficacy on performing a motor task is largely influenced by the knowledge of performance and results [51, 52], and feedback on concurrent performance can be used to improve self-confidence in performance and quality of performance [51].

B. Effects of Side View

Results revealed secondary gait changes that are specific to the side view of the real-time avatar, which included larger paretic and non-paretic step length, faster walking speed and, in the majority of participants displaying a larger paretic step length to start with, improvements in step length symmetry. A possible reason for participants performing better in the side view condition vs. back and frontal view could be that the side view offered optimal visual feedback on step length as well as lower limb sagittal joint amplitude compared to the other two views. Similarly, healthy participants in another recent study [38] recognized tasks such as punching and kicking faster in a profile (side) view compared to frontal view, suggesting that the profile view (side view) provided more motion information for discernment [38]. The positive changes in gait that were observed for the side view in the present study were also consistent with the fact that this view was the most subjectively preferred view by participants. Interestingly, three out of five participants who reported of preferring the side view were also the responders of step length ratio improvement during the adaptation and post-adaptation phases in the side view.

C. Spatial vs Temporal Changes

Positive changes in the spatial domain induced by the side view feedback were not necessarily consistent with changes in the temporal domain. For example, the bilateral increase in step length that was observed with the side view led to faster walking speed, despite an increase in swing time on the paretic side. Furthermore, improvements in symmetry, when present, were observed for step length but not for swing time. The increase in bilateral step length is possibly due to the attempt of participants to correct their spatial symmetry, and we suggest that the increase in walking speed can also be seen as a result of such attempt. Such changes may have taken place at the expense of temporal parameters because in order to take a longer step, people with stroke may require a longer swing time.

The mechanisms in which spatial and temporal changes occur are also different. Vision is the sensory modality that is the most relied upon among humans to perceive spatial information, and it is essential for people to master the spatial aspects of a movement [53]. On the other hand, sounds and auditory feedback provide more information about the temporal aspect of a movement [54]. This is evidenced by healthy participants learning a rowing task, where auditory feedback could provide information about the temporal aspect of a movement and help performers in the advanced stages of learning to fine-tune their movement execution [54]. The same study also concluded that the groups receiving visual feedback had the least spatial error compared to haptic and auditory feedback after three training sessions [54]. Since only visual feedback was used in the avatar-based modality in this study, this could explain why the temporal asymmetry was not significantly changed in any view condition. Therefore, to improve the temporal aspect of gait asymmetry, only visual feedback might not be enough, and the auditory feedback would be a necessary addition to the avatar-based intervention.

D. Responders vs Non-responders in Spatial Symmetry

There were noticeable differences between the responders and non-responders of spatial symmetry improvement in the adaptation phase of the side view. First, the responders all had a larger paretic step length while the non-responders had a larger non-paretic step length, in agreement with a previous study [55]. There are possible reasons that could explain why this happened. As demonstrated from the results, the step length on the non-paretic side was increased to a significantly larger extent than the paretic side during adaptation for all participants. As mentioned previously, in an attempt to improve their spatial symmetry, the participants always tried to take larger steps, but since their paretic side was less functional than the non-paretic side, their paretic step length was increased to a lesser extent than the non-paretic step length. As a result, if the initial shorter step is on the non-paretic side, the spatial symmetry is improved, otherwise it is worsened. In addition, a previous study on gait analysis of people with chronic stroke reported that people with a longer paretic step length generated the least amount of propulsive force with the paretic leg compared to people with either symmetrical step length or longer non-paretic step length, and that asymmetry in step lengths is strongly related to asymmetry in propulsive forces [12]. Therefore, the responders of this study might have generated greater propulsive force with their paretic leg in an attempt to improve the spatial symmetry, but additional research would be needed to confirm this. Another explanation could be the fact that the side view was always portrayed on the paretic side in this experiment. It is possible that people with a larger non-paretic step length would respond better to a non-paretic side view, so for these participants the paretic side view might not provide the necessary information for them to improve their spatial asymmetry.

The responders and non-responder might also have different preferences for biofeedback. In a study of gait training with avatar among children with cerebral palsy, it was stated that although the majority of children preferred biofeedback in the form of avatar, some considered feedback shown in bar style easier to understand [56]. It was possible that self-perception of walking, cognitive ability and previous experience with biofeedback were the factors that influenced the children’s preference [56]. Similarly, these factors could also explain why some of the participants with stroke benefited from the biofeedback in the form of avatar while others did not in our study.

The responders had a significantly higher average CMSA foot score compared to the non-responders. This could suggest that
a higher functional level makes correcting spatial asymmetry easier as the participants would have stronger control on their paretic step length. On the other hand, no significant difference was noted between responders and non-responders in terms of their initial step length ratio. In a previous study of Patterson and colleagues (2015), it was found that the participants who improved their spatial symmetry had worse initial step length ratio than those who did not change or deteriorated, but the authors did not report if this difference of initial step length ratio was statistically significant [18]. Further research would be needed to examine the relationship between the initial level of asymmetry and the likelihood to improve gait symmetry. It should also to be noted that all responders in the adaptation phase maintained their improvement once the stimulus was removed (post-adaptation phase).

E. Increase in Treadmill Walking Speed and Its benefits

Another interesting finding is the increase in walking speed during the avatar exposure, which took place despite of the fact that participants were not instructed to walk faster during the experiment. Increasing walking speed through an increase in step length itself can be clinically beneficial for people with stroke. It has been shown that compared to healthy people, people with stroke tend to have a much smaller step length [57]. Although it is still not fully understood why people with stroke usually have shorter step length, it is possibly caused by fear of falling because taking small ‘shuffle’ steps can be interpreted as being cautious. In addition, the outcomes ‘walking speed’ and ‘paretic step length’ also showed significant retention effects in the post-adaptation phase, and this further demonstrated the fact that even with a very short duration of training, the avatar-based intervention can be an effective tool to improve the spatial aspect of the gait of the people with stroke.

F. Limitations

A primary limitation of this study is the short duration of the trials where the exposure was limited to 1 min. This time period was chosen considering the number of walking trials needed and limited endurance of the participants. However even with a short exposure duration, we were able to demonstrate statistically significant changes in treadmill walking speed, bilateral step length and paretic swing time in the adaptation phase. Possibly larger changes would be observed with longer as well as repeated exposures to avatar-based feedback. Another limitation is the small sample size in relation to the different types of asymmetries present in our sample. In a study of prevalence of gait asymmetry among people with chronic stroke, it was shown that 55.5% participants exhibited temporal asymmetry, and only 33.3% had spatial asymmetry [58]. Therefore, it is difficult to recruit a large number of participants from both categories of asymmetry due to the low prevalence. The information provided through this study, however, provides important indications as to who may best benefit from avatar-based feedback as a potential intervention for gait asymmetries following stroke.

V. Conclusion

In conclusion, the following statements can be made based on the results and analyses: (1) Real-time visual feedback provided by an avatar in the paretic side view is a feasible and acceptable intervention to elicit immediate positive changes in walking speed, and spatial asymmetry for people with a chronic stroke; (2) The side view is the only condition that demonstrated significant increase in walking speed, paretic and non-paretic step length; (3) There is also a retention effect of improvement in walking speed, paretic step length and responders of step length ratio in the side view during the post-adaptation phase where the feedback is removed; (4) Having a larger paretic step length and a greater CMSA foot score (better motor recovery) lead to a larger improvement in spatial symmetry. Overall, the real-time avatar-based feedback can provide many advantages as a gait training intervention: it is versatile because avatars and the scenes can be modified according the need of different participants; it received overwhelming positive feedback from the participants as it is engaging and intuitive; and most importantly, it provides unique concurrent information on walking performance that would otherwise be very difficult or even impossible for clinicians to deliver. In the future, clinical trials with longer and multiple training sessions are needed to test the applicability of avatar-based feedback in the clinical setting. Auditory feedback such as footstep sounds could also be incorporated to examine its effectiveness on temporal symmetry.

Disclosure

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