Gait & Posture 67 (2019) 251–256

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Gait adaptations during overground walking and multidirectional oscillations of the visual field in a virtual reality headset

Dario Martelli[a,*,1], Boxi Xia[a,1], Antonio Prado[a], Sunil K. Agrawal[a,b,*]

[a] Department of Mechanical Engineering, Columbia University, New York, United States
[b] Department of Rehabilitation and Regenerative Medicine, Columbia University College of Physicians and Surgeons, New York, United States

ARTICLE INFO

Keywords:
Virtual reality
Gait
Perturbations
Overground
Adaptation
Balance

ABSTRACT

Background: Virtual reality (VR) has been used to study locomotor adaptability during balance-demanding tasks by exploring how humans react and adapt to the virtual environment (VE) and discordant sensorimotor stimulations. Previous research primarily focused on treadmill walking and little is known regarding the propensity for gait adaptations during overground walking and over time.
Research question: To what extent healthy young adults modify and adapt gait during overground walking in a VE and with continuous multidirectional perturbations of the visual field while wearing a VR headset?
Methods: Twelve healthy young adults walked for 6 min on an instrumented walkway in four different conditions: RE, VE, and VE with antero-posterior (AP) and medio-lateral (ML) pseudo-random oscillations of the visual field. For each condition, stride length (SL), stride width (SW), stride time (ST) and their variability (SLV, SWV, and STV) were calculated using one-minute walking intervals. A 2-way repeated-measures ANOVA was performed to determine the main and interaction effects of the walking conditions and time.
Results: Participants took shorter SL and showed higher SWV while walking in the VE. Perturbations of the visual field resulted in reduced SL, larger SW, and higher stride variability (i.e., SLV, SWV, and STV). The response was anisotropic, such that effects were more pronounced during the ML compared to AP perturbations. Over time, participants adapted to the VE and the visual perturbations by increasing SL and reducing SW, SLV, STV, and ST (only during VE and ML conditions). SWV did not adapt over time.
Significance: The paper provided first evidence for visuomotor adaptations during unperturbed overground walking and during visual perturbations while wearing a VR headset. It represents an initial investigation that may help the development of new VR methods for early detection and remediation of gait deficits in more ecological conditions.

1. Introduction

Bipedal walking is a complex motor task that consists of three primary components: locomotion, balance, and ability to adapt to the environment [1]. The integration of sensory information from the visual, vestibular and somatosensory systems are essential to compensate for instabilities [2]. A deterioration in the quality of sensory integration results in gait deficits [3], a common problem among the elderly and those with neuromusculoskeletal disorders [1,4]. Research on locomotor adaptability during simulated balance-demanding tasks could lead to effective methods to early identify and remediate gait deficits.

Recent advancements in the technology of virtual reality (VR) has allowed access to unexplored paradigms [5,6]. VR provides a safe environment for analyzing how humans react and adapt to the virtual environment (VE) and various types of discordant sensorimotor stimulations [7,8]. Sensory discordances in the form of oscillations of the visual field are of particular interest because they allow to study the reliance on visual feedback and the propensity for visuomotor adaptations while challenging the ability to maintain balance during walking [2,9–11]. Locomotor adaptability and sensorimotor remapping could reduce the perceived discordance [12,13]. However, little is known to what extent humans can modify their walking pattern over time to accommodate the VE [14,15] and the visual perturbations [16]. In addition, gait modifications and adaptations have been previously studied using fixed screens (i.e., VR domes) while walking on a treadmill [2,9,16].

* Corresponding authors at: Department of Mechanical Engineering, Columbia University, 220 S.W. Mudd Building, 500 West 120th Street, New York, NY, 10027, USA.
E-mail addresses: dm3042@columbia.edu (D. Martelli), sa3077@columbia.edu (S.K. Agrawal).
[1] Equal Contributors.

https://doi.org/10.1016/j.gaitpost.2018.10.029
Received 25 January 2018; Received in revised form 24 October 2018; Accepted 25 October 2018

Treadmill training offers several advantages in a laboratory setting. However, whether treadmill walking induces identical motor responses of overground walking is equivocal [17]. Although self-paced treadmills with VR has been used to minimize the issue of imposed walking speed and lack of optic flow, gait does not completely approximate overground walking even after long periods of familiarization [14,18]. As a result, locomotor skills gained during treadmill training may still be difficult to translate in overground walking [17]. Accordingly, some treadmill-based gait training paradigms have considered the integration of overground components to reinforce the intervention and maximize transfer of the skills to real-world conditions [19].

New advances in real-time tracking, display, and networking capabilities allowed the development of commercially-available head-mounted displays with room-scale tracking (i.e., VR headsets). VR headsets are designed to: (i) provide immersive binocular depth cues using stereoscopic displays and first-person view that can better elicit visual responses; (ii) allow the user to navigate naturally in increasingly larger spaces, thus allowing to move to overground-based interventions; and (iii) offer a portable and cheaper alternative to the VR domes. Using VR headsets during overground walking enables the study of locomotor adaptations in the VE and to visual perturbations in a more ecological setting. Research in this field is relatively new: little is currently known about how walking overground with a VR headset resemble gait in the real environment (RE) [20,21] and how humans react and adapt to visual perturbations [22].

This pilot study aims to investigate modifications and propensity for visuomotor adaptations of spatio-temporal gait parameters due to prolonged walking in a VE, and during continuous antero-posterior (AP) and medio-lateral (ML) oscillations of the visual field. We hypothesized that: (i) participants would show small differences in gait characteristics between the real and the virtual environments; (ii) exposure to continuous visual perturbations would affect gait and its variability, with greater effect of ML perturbations compared to AP ones [9]; and (iii) the prolonged exposure to these conditions would lead to locomotor adaptations that would reduce differences in the gait [16].

2. Methods

Twelve healthy young adults participated in the experiment (8 males, 24.8 ± 3.7 years old, 74.9 ± 14.3 kg, 1.74 ± 0.09 m). Subjects were informed about the research procedure and signed a written consent form approved by the Institutional Review Board of Columbia University, before participating. All participants had normal or corrected-to-normal vision. During the experiment, six participants wore glasses. None of the participants had any reported disorder and all were naïve to the experimental conditions.

Participants walked for 6 min on a $6m \times 0.6m$ instrumented walkway (Zeno Walkway, Protokinetics) at their comfortable speed in four different conditions. First, they walked in the real environment (RE). Then, they wore a VR headset (HTC VIVE), and they walked in the virtual environment (VE). A Unity3D program was developed to display a virtual walkway within the VR headset. The VE was calibrated so that the virtual walkway was aligned and mapped one-to-one with respect to the physical walkway. The visual stimulus was a 3D outdoor space; objects such as trees and animals were placed to provide depth reference (Fig. 1). Participants experienced a first-person view of themselves walking in the virtual walkway without corresponding movements of their self-representation (i.e., their body was not rendered in the VE). Finally, participants walked in the VE while experiencing medio-lateral (ML) or antero-posterior (AP) visual perturbations. The order of the presentation of the AP and ML conditions was balanced across participants to account for potential learning effects. Perturbations were delivered by superimposing oscillations of the visual field on top of the normal visual flow. Oscillations were applied as a pseudo-random sum of sines with four frequencies, as proposed in a previous experiment during treadmill walking [9], using the following equation:

$$D(t) = A\,[\sin(0.16\cdot 2\pi t) + 0.8\sin(0.21\cdot 2\pi t) + 1.4\sin(0.24\cdot 2\pi t) + 0.5\sin(0.49\cdot 2\pi t)] \quad (1)$$

where $D(t)$ is the superimposed displacement of objects [m] that participants perceived in the VE during perturbations, A is a scaling factor equal to 0.5, and t is time [s].

Each condition with the headset was followed by a 3-min RE walking condition to washout possible aftereffects of VR. Participants were aware that they might be perturbed in the AP or ML conditions but were unaware of the magnitude, the direction, or the timing of the perturbations. Before the intervention started, they were instructed to maintain balance and keep walking. Participants were allowed to take breaks at any time between the sessions to minimize the effects of exhaustion or lack of concentration.

Spatiotemporal gait parameters were measured at 120 HZ using the PKMAS gait recording and analysis software of the walkway. Stride length (SL), stride width (SW), and stride time (ST) were calculated at both left and right heel strikes. SL was defined as the distance between the corresponding successive heel points of the same foot, measured parallel to the direction of progression. SW was calculated as the perpendicular distance between the line connecting the two ipsilateral foot heel points and the contralateral heel point. ST was estimated as the time period between the first consecutive contact of the same foot. Data points were excluded in case participants stepped out of the walkway or the software was unable to recognize two different steps. For each condition (i.e., RE, VE, ML, and AP), outcomes were calculated for 30 random strides over each minute of walking. This was necessary to guarantee that the same number of strides was taken for all subjects during each condition and minute of walking. Means and standard deviations were calculated to estimate representative strides (SL, SW and ST) and overall variability (SLV, SWV and STV), respectively.

A two-way repeated-measures analysis of variance (rmANOVA) was performed to determine main and interaction effects of walking condition (4 levels: RE, VE, ML, AP) and time (6 levels: minutes 1–6). Interaction effects were followed up by one-way rmANOVAs performed individually on each condition (with time as the only factor). If significant, effects were followed up by pairwise comparisons with Benjamini-Hochberg correction. For the time factor, planned comparisons were made between the first and the other minutes of walking. The Lilliefors and Mauchly's tests were performed to check the normality and sphericity assumptions of data. The Huynh-Feldt correction was applied if data violated the sphericity condition. Statistical significance was set at $p < .05$. Statistical analysis was performed using SPSS version 25.

3. Results

All participants completed the experiment without difficulties. Figs. 2 and 3 show SL, SW, ST and their variabilities for each condition and minute of walking. Table 1 reports the results of the statistical analysis. Except for ST, all outcomes showed significant main effects of condition. Except for SWV, all outcomes exhibited significant main effects of time. SL, ST and STV showed a significant condition × time interaction term. The one-way rmANOVAs showed a significant effect of time for: (i) SL and STV in all conditions except for RE ($p \le .030$); and (ii) ST for the VE ($p = .003$) and ML ($p = .043$) conditions.

While walking in the VE, participants took significantly shorter strides (VE: 134.5 ± 7.8 mm; RE: 140.4 ± 7.8 mm, $p = .011$, Fig. 2A) with higher SWV (VE: 2.6 ± 1.0 mm; RE: 2.3 ± 0.8 mm, $p = .012$, Fig. 3B) than in the RE. SLV showed a trend to be higher during VE walking, but significance level was not reached (VE: 5.7 ± 2.2 mm; RE: 4.6 ± 1.8 mm, $p = .052$, Fig. 3A). SW (VE: 7.5 ± 3.5 mm; RE: 7.4 ± 3.1 mm, Fig. 2B), ST (VE: 1.11 ± 0.10 s; RE: 1.08 ± 0.06 s, Fig. 2C), and STV (VE: 0.04 ± 0.02 mm; RE: 0.03 ± 0.02 s, Fig. 3C) were similar between VE and RE ($p \ge .157$). While walking in the VE, a significant effect of time was found for SL, ST, and their variability.

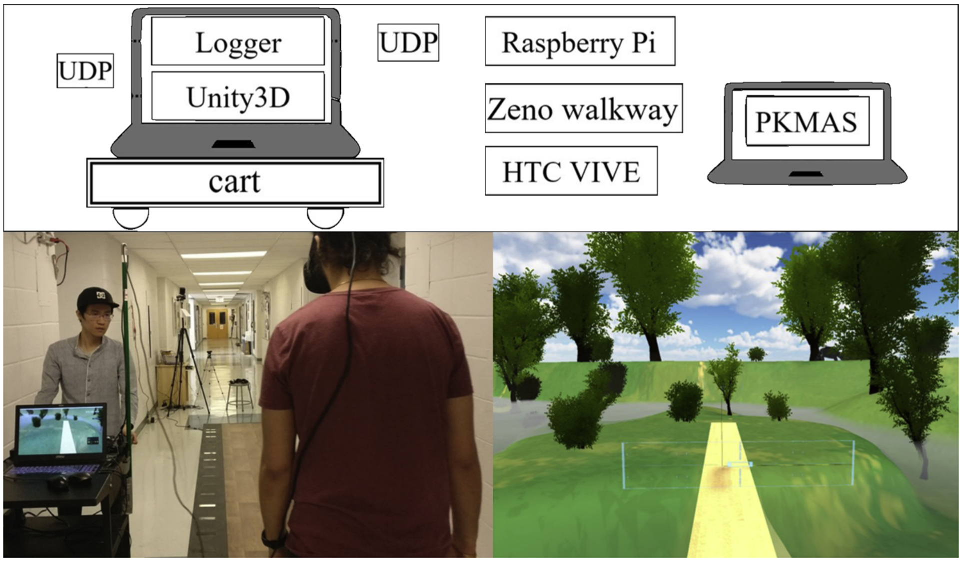

Fig. 1. Experimental Setup.
Schematic of the system (top). Picture of a subject walking with the headset (bottom left). View of the virtual environment (bottom right). For rendering, system control, and logging, we used an Intel computer with 3.4 GHz Core i7 processor, 16GB of main memory, and NVIDIA GeForce GTX 1060 graphics card. The participants wore VIVE headset for the stimulus presentation, which provides a resolution of 2160 × 1200 pixel per eye with a refresh rate of 90 Hz and a 110° diagonal field of view. Two cameras were used to detect the position and orientation of the headset at an update rate of 120 Hz with sub-millimeter precision and accuracy for position data. In order to keep the headset cables from getting tangled with the participant and provide comfort to the head from the weight of the cables, the headset computer was placed on a cart and an experimenter followed the participant while walking. In the VE, the virtual ground was aligned with the global x–z plane, and the global y-axis pointed upward. On the ground was a virtual walkway, with its walking direction aligned with the global z-axis.

Over time, participants took longer, faster and less variable strides. After adjusting the alpha level for multiple comparisons, significant differences were observed between: (i) minute 1 and minutes 5–6 for SLV ($p \leq .004$); (ii) minute 1 and minutes 2–6 for ST ($p \leq .015$); and (iii) minute 1 and minutes 3–6 for STV ($p \leq .007$).

Independently by the direction of the oscillations, participants took significantly shorter (AP: 126.4 ± 7.8 cm; ML: 112.1 ± 19.8 cm, $p \leq .003$, Fig. 2A) and wider (AP: 9.4 ± 3.1 cm; ML: 11.0 ± 3.5 cm, $p \leq .002$, Fig. 2B) strides with higher SLV (AP: 8.1 ± 5.0 cm; ML: 13.8 ± 8.2 cm, $p \leq .006$, Fig. 3A), SWV (AP: 3.2 ± 1.8 cm, ML: 6.4 ± 3.2 cm, $p \leq .012$, Fig. 3B) and STV (AP: 0.05 ± 0.04 s; ML: 0.11 ± 0.10 s, $p \leq .036$, Fig. 3C) during perturbed (i.e., AP and ML) than unperturbed walking (i.e., RE and VE). The only exceptions were for SWV and STV, which were similar between AP and VE conditions ($p \geq .065$). SL and STV showed a significant effect of time during both AP and ML ($p \leq .030$, Figs. 2A and 3 C) perturbations. Participants increased SL and reduced STV over time. Pairwise comparisons showed differences in SL between minute 1 and minutes 2–6 ($p \leq .044$) during both AP and ML perturbations and differences in STV between minute 1 and minute 6 ($p \leq .043$) during AP perturbations.

ML perturbations caused greater reductions in SL ($p = .003$, Fig. 2A) and increments in SW ($p = .012$, Fig. 2B) and stride variability ($p \leq .006$, Fig. 3) than AP perturbations. ST showed a significant effect of time during ML perturbations ($p = .043$, Fig. 2C). Opposed to all the other outcomes that showed a return towards value seen during normal walking, ST decreased over time.

Independently by the condition, SW ($p = .012$, Fig. 2B) and SLV ($p < .001$, Fig. 3A) showed a significant effect of time. Pairwise comparisons clarified that: (i) SW was significantly wider during the first minute than the others ($p \leq .018$); and (ii) SLV was significantly higher during the first minute than minutes 3–6 ($p \leq .006$).

4. Discussion

This study aimed to analyze gait modifications within a virtual environment while walking overground and while walking and reacting to multidirectional perturbations of the visual field. Moreover, we wanted to investigate the adaptations of gait over time due to prolonged exposure to these conditions. While these effects are known for treadmill walking, to the best of our knowledge, this is the first study that analyzes the effect of visual perturbations and the prevalence of visuomotor adaptation during unperturbed overground walking or in response to continuous visual oscillations in a VR headset.

Previous studies showed contradicting results regarding modifications of spatiotemporal gait parameters and their variability as an effect of VR [15,20,23–26]. These inconsistencies suggest that gait modifications highly depend on the specific set-up (i.e., VR domes or headset), mode of walking (i.e., self-paced treadmill, fixed speed treadmill, or overground walking), quality of the image (e.g., frame rate update, resolution, field of view, accuracy, etc.), and time given to adapt to the new environment. In regards to overground walking with a VR headset, previous studies showed that healthy young adults walk in the VE with reduced stride lengths, increased step widths and longer stride times [20,21]. No results have been reported on the modifications of stride variability. Moreover, the authors constrained the analysis for the first two laps of walking on the walkway, thus taking into account only acute modifications of gait during the first few strides in the VE. Perhaps, it is necessary to give participants enough time to familiarize with the VE in order to reduce differences between the real and virtual environments. Indeed, we found that, except for SWV, all outcomes showed a significant effect of time while walking in the VE. Because of this, initial differences were reduced over time. Despite that, participants still took shorter strides with higher stride width variability while walking in the VE. Some justifications for the dissimilarities may be the smaller field of view, the misinterpretation of the distance due to incorrect depth cues provided to the human eye and the lack of visual information about self-motion when looking through the VR headset [20].

As expected, the exposure to continuous pseudorandom oscillations of the visual field caused significant disruption of the gait pattern. Perturbations were associated with reduced stride length and increased stride width and stride variability. Results were generally in accordance with previous experiments while walking on a treadmill at fixed speed [9] and support the validity of these setups in studying perturbed gait. The only differences were that we did not find any effect of ML and AP perturbations on ST and SWV, respectively. Additionally, our results highlighted a significant effect of time for ST during ML perturbations. We cannot exclude that the observed reduction in ST would have made significant the condition factor by exposing participants for a longer time to the perturbations. Despite the trend of SWV to be higher during AP perturbations than VE walking, we found significant differences only with respect to the RE. Our results suggest that increments in SWV are due to the VE [23] and AP perturbations have low effect in modifying SWV [27].

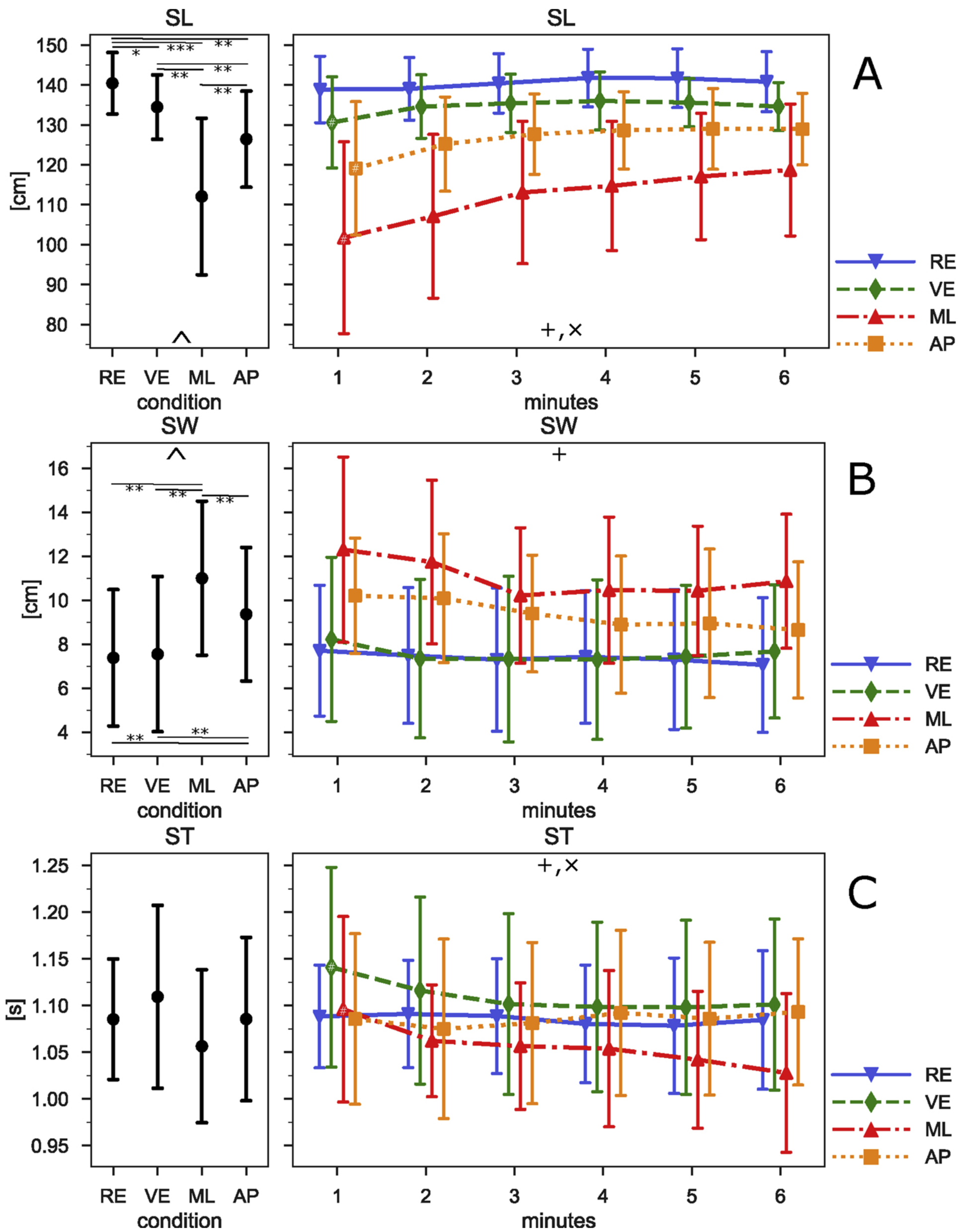

Fig. 2. Results: Mean Gait Parameters.
Panel A. Stride length (SL). Panel B. Stride Width (SW). Panel C: Stride Time (ST). Left and right graphs represent the effect of condition and time, respectively. On the left graphs each point represents the mean value among the six minutes of walking for the real environment (RE), virtual environment (VE), Medio-Lateral perturbations (ML) and Antero-Posterior perturbations (AP). On the right graphs, each line represents a different condition at each minute of recording (minute 1 to minute 6) during overground walking for RE (blue lines), VE (green lines), ML (red lines), and AP (purple lines). Error bars refer to standard deviations. ˆ, + and × symbols indicate a significant condition, time and interaction effects of the two-way rmANOVA. # symbols inside markers at minute 1, indicate a significant effect of time of the one-way rmANOVA. * symbols indicate a significant difference between conditions as result of the pairwise comparisons (*$p < .050$, **$p < .010$, ***$p < .010$). Values are reported as mean ± one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The response was anisotropic, such that participants took shorter, wider and more variable strides during the ML than the AP perturbations. The AP perturbations visually superimposed a velocity to the forward walking velocity whereas ML perturbations superimposed a sideway velocity in a direction orthogonal to walking. Thus, AP perturbation could be less perceivable than ML perturbation [9]. Also, walking balance in ML direction is considered inherently more demanding than in AP direction [28]. Walking is passively unstable in the ML direction, which requires step-by-step, integrative control, whereas in the AP direction, balance is passively stabilized through a series of controlled falls [2].

Results showed that participants modified SL, SW, ST and their variability (except SWV) over time. Multisensory reweighting might explain the adaptation in visual perturbation [16]. In the beginning, the discrepancy between the visual and other sensory feedback could cause subjects to walk in a disoriented way. Over time, participants may have down-weighted the contribution of the vision and relied more on vestibular and other sensory feedback for balancing. Previous authors found increments of step width variability, and inability to modify step width or step length variability over time while reacting to sinusoidal ML perturbations during treadmill walking at fixed speed [16]. We found significant modifications of SLV, small modifications of stride width while considering all conditions together (but not while considering ML perturbations alone) and no effect of time on SWV. Discrepancies may be due to the type of perturbation used or by the fact that visuomotor adaption follows a different mechanism for treadmill compared to overground walking. Sinusoidal perturbations may result in individuals predicting the perturbations and entraining to it [10], and treadmill walking is already characterized by gait modifications with respect to overground walking [14].

The present pilot study represents an initial investigation on a topic of possible interest for the scientific and clinical community and may have positive implications for early detection and remediation of gait disorders. Sensory acuity often deteriorates with aging. Previous experiments showed that visual perturbations affect gait in older adults more than healthy young subjects [29,30] thus highlighting their increased reliance on visual feedback to maintain balance. Moreover, magnitudes of aftereffects in the real environment are correlated with the rate of adaptation during the periods of sensorimotor discordance [7]. Similar to what was already done for improving the reaction to

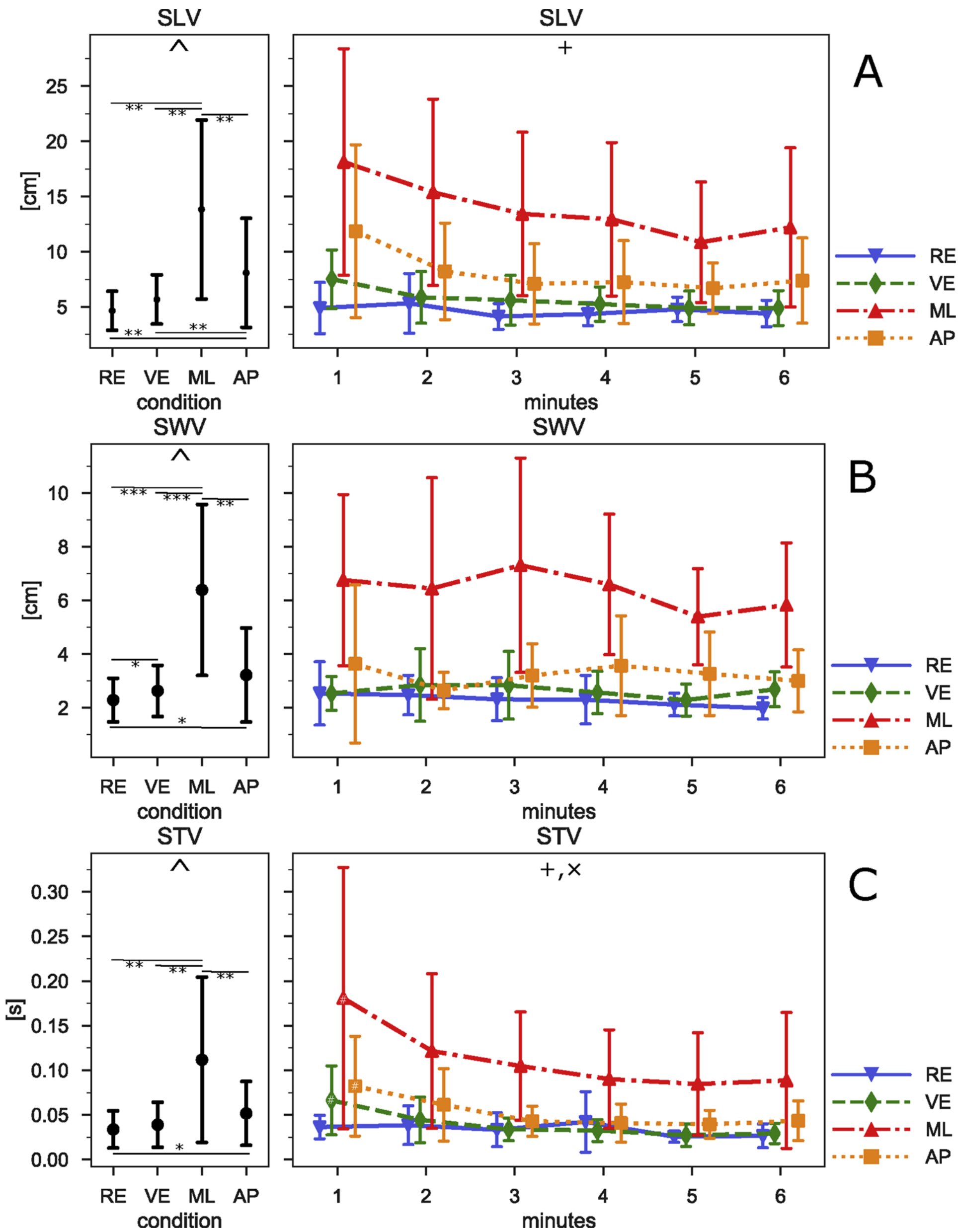

Fig. 3. Results: Gait Variability.
Panel A. Stride length variability (SLV). Panel B. Stride Width Variability (SWV). Panel C: Stride Time Variability (STV). Left and right graphs represent the effect of condition and time, respectively. On the left graphs each point represents the mean value among the six minutes of walking for the real environment (RE), virtual environment (VE), Medio-Lateral perturbations (ML) and Antero-Posterior perturbations (AP). On the right graphs, each line represents a different condition at each minute of recording (minute 1 to minute 6) during overground walking for RE (blue lines), VE (green lines), ML (red lines), and AP (purple lines). Error bars refer to standard deviations. ˆ, + and × symbols indicate a significant condition, time and interaction effects of the two-way rmANOVA. # symbols inside markers at minute 1, indicate a significant effect of time of the one-way rmANOVA. * symbols indicate a significant difference between conditions as result of the pairwise comparisons (*$p < .050$, **$p < .010$, ***$p < .010$). Values are reported as mean ± one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
p-values of the results of the statistical tests. Outcome Variables: Step Length (SL); Stride Width (SW); Stride Time (ST) and their variabilities (V). Conditions (C): Real Environment (RE); Virtual Environment (VE); Medio-Lateral perturbations (ML); Antero-Posterior perturbations (AP). When the *p*-value is statistically significant, it is highlighted in bold.

Statistical Tests		Outcome Variables					
		SL	SLV	SW	SWV	ST	STV
2-way rmANOVA (Condition × Time)	C	< **.001**	< **.001**	< **.001**	< **.001**	.167	**.001**
	T	< **.001**	< **.001**	**.012**	.195	**.016**	< **.001**
	C × T	< **.001**	.164	.196	.468	**.015**	**.010**
1-way rmANOVA (Time)	RE	.191	.357	.184	.237	.610	.245
	VE	**.015**	**.004**	.142	.538	**.003**	**.002**
	ML	**.002**	**.031**	.120	.273	**.043**	**.014**
	AP	**.007**	.100	**.006**	.406	.495	**.030**
Pairwise Comparisons Condition (C)	RE – VE	**.011**	.052	.569	**.012**	.165	.157
	RE – ML	**.000**	**.001**	**.001**	**.000**	.251	**.002**
	RE – AP	**.001**	**.002**	**.001**	**.012**	.992	**.036**
	VE – ML	**.001**	**.001**	**.001**	**.000**	.105	**.003**
	VE – AP	**.003**	**.006**	**.002**	.065	.303	.086
	ML – AP	**.003**	**.002**	**.012**	**.003**	**.046**	**.006**

slipping perturbations using a treadmill visual-perturbation training [11], an over-ground training paradigm with continuous visual perturbations could be proposed to train subjects to refine the relative weighting of different sensory feedbacks, through the exposure to visual perturbation in a more ecological condition.

The study has several limitations. The VR system was only able to track a limited area, which restricted the longest distance a subject could walk continuously in the hallway. The width of the Zeno Walkway was relatively narrow such that we were not able to apply perturbations of greater magnitudes to avoid participants walking out of the mat. The experiment was performed by a small sample of healthy young adults, and the results are not generalizable for other population groups. However, the analysis of the behavior of healthy young adults is the first and necessary step to identify an approach to base further studies on other population groups targeted for screening and training. This approach can potentially be used to improve gait and reduce the number of falls in persons with balance impairments. Further studies involving larger samples of older adults or patients with balance disorders are necessary to test the usability of this approach for diagnostic and training purposes. Future studies will also analyze how the exposure to continuous visual perturbations can create aftereffects during RE walking and to what extent displaying self-representation of motion affects the obtained outcomes.

Author contributions

DM and SKA conceptualized the study and supervised the project. DM, BX, and AP designed the study and collected the data. BX and AP worked on the hardware and software of the system. BX cleaned and analyzed the data. DM performed the statistical analysis. DM and BX prepared a first draft of the manuscript and created the figures and tables. All authors contributed extensively to the work presented in this paper, commented on the manuscript throughout the editorial process, and approved the final submitted version.

Conflict of interest

This research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

This work was supported by the National Science Foundation [grant number: NSF IIS-1339666]; and the New York State Department of Health [grant numbers: NYS Translational GrantC31290GG, NYS Institutional SupportC32238GG, NYS Individual Postdoctoral FellowshipC32632GG to DM], which had no role in design, execution, analysis or writing of this study.

References

[1] A.H. Snijders, B.P. van de Warrenburg, N. Giladi, B.R. Bloem, Neurological gait disorders in elderly people: clinical approach and classification, Lancet Neurol. 6 (2007) 63–74.
[2] S.M. O'Connor, A.D. Kuo, Direction-dependent control of balance during walking and standing, J. Neurophysiol. 102 (2009) 1411–1419.
[3] G. Abbruzzese, A. Berardelli, Sensorimotor integration in movement disorders, Mov Disord. 18 (2003) 231–240.
[4] J. Verghese, A. LeValley, C.B. Hall, M.J. Katz, A.F. Ambrose, R.B. Lipton, Epidemiology of gait disorders in community-residing older adults, J. Am. Geriatr. Soc. 54 (2006) 255–261.
[5] H. Sveistrup, Motor rehabilitation using virtual reality, J. Neuroeng. Rehabil. 1 (2004) 10.
[6] S.V. Adamovich, G.G. Fluet, E. Tunik, A.S. Merians, Sensorimotor training in virtual reality: a review, NeuroRehabilitation 25 (2009) 29–44.
[7] J.T. Richards, A.P. Mulavara, J.J. Bloomberg, The interplay between strategic and adaptive control mechanisms in plastic recalibration of locomotor function, Exp. Brain Res. 178 (2007) 326–338.
[8] T. Prokop, M. Schubert, W. Berger, Visual influence on human locomotion. Modulation to changes in optic flow, Exp. Brain Res. 114 (1997) 63–70.
[9] P.M. McAndrew, J.B. Dingwell, J.M. Wilken, Walking variability during continuous pseudo-random oscillations of the support surface and visual field, J. Biomech. 43 (2010) 1470–1475.
[10] J.R. Franz, C. Francis, M. Allen, D.G. Thelen, Visuomotor Entrainment and the Frequency-Dependent Response of Walking Balance to Perturbations, IEEE Transactions on Neural Systems and Rehabilitation Engineering: A Publication of the IEEE Engineering in Medicine and Biology Society, 2016.
[11] P. Parijat, T.E. Lockhart, J. Liu, Effects of perturbation-based slip training using a virtual reality environment on slip-induced falls, Ann. Biomed. Eng. 43 (2015) 958–967.
[12] W.G. Wright, Using virtual reality to augment perception, enhance sensorimotor adaptation, and change our minds, Front. Syst. Neurosci. 8 (2014).
[13] S. Bohm, L. Mademli, F. Mersmann, A. Arampatzis, Predictive and Reactive locomotor adaptability in healthy elderly: a systematic review and meta-analysis, Sports Med. 45 (2015) 1759–1777.
[14] M. Schellenbach, M. Lovden, J. Verrel, A. Kruger, U. Lindenberger, Adult age differences in familiarization to treadmill walking within virtual environments, Gait Posture 31 (2010) 295–299.
[15] P. Parijat, T.E. Lockhart, Can virtual reality be used as a gait training tool for older adults? Human Factors and Ergonomics Society 55th Annual Meeting (2011) 157–161.
[16] J.D. Thompson, J.R. Franz, Do kinematic metrics of walking balance adapt to perturbed optical flow? Hum. Mov. Sci. 54 (2017) 34–40.
[17] J.H. Hollman, M.K. Watkins, A.C. Imhoff, C.E. Braun, K.A. Akervik, D.K. Ness, A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions, Gait Posture 43 (2016) 204–209.
[18] M.M. van der Krogt, L.H. Sloot, J. Harlaar, Overground versus self-paced treadmill walking in a virtual environment in children with cerebral palsy, Gait Posture 40 (2014) 587–593.
[19] L. Bishop, M. Khan, D. Martelli, L. Quinn, J. Stein, S. Agrawal, Exploration of Two training paradigms using forced induced weight shifting with the tethered pelvic assist device to reduce asymmetry in individuals after stroke: case reports, Am. J. Phys. Med. Rehabil. Assoc. Acad. Physiatrists (2017).
[20] O. Janeh, E. Langbehn, F. Steinicke, G. Bruder, A. Gulberti, M. Poetter, et al., walking in virtual reality: effects of manipulated visual self-motion on walking biomechanics, ACM Trans. Appl. Percept. 14 (2017) 1–15.
[21] B.J. Mohler, J.L. Campos, M.B. Weyel, H.H. Bülthoff, Gait parameters while walking in a head-mounted display virtual environment and the real world, Proceedings of the 13th Eurographics Symposium on Virtual Environments (2007).
[22] L. Nyberg, L. Lundin-Olsson, B. Sondell, A. Backman, K. Holmlund, S. Eriksson, et al., Using a virtual reality system to study balance and walking in a virtual outdoor environment: a pilot study, Cyberpsychol. Behav. 9 (2006) 388–395.
[23] J.H. Hollman, R.H. Brey, R.A. Robb, T.J. Bang, K.R. Kaufman, Spatiotemporal gait deviations in a virtual reality environment, Gait Posture 23 (2006) 441–444.
[24] L.H. Sloot, M.M. van der Krogt, J. Harlaar, Effects of adding a virtual reality environment to different modes of treadmill walking, Gait Posture 39 (2014) 939–945.
[25] M.A. Sheik-Nainar, D.B. Kaber, The utility of a virtual reality locomotion interface for studying gait behavior, Hum. Factors 49 (2007) 696–709.
[26] D. Katsavelis, M. Mukherjee, L. Decker, N. Stergiou, The effect of virtual reality on gait variability, Nonlinear Dyn. Psychol. Life Sci. 14 (2010) 239–256.
[27] S.M. O'Connor, H.Z. Xu, A.D. Kuo, Energetic cost of walking with increased step variability, Gait Posture 36 (2012) 102–107.
[28] C.E. Bauby, A.D. Kuo, Active control of lateral balance in human walking, J. Biomech. 33 (2000) 1433–1440.
[29] C.A. Francis, J.R. Franz, S.M. O'Connor, D.G. Thelen, Gait variability in healthy old adults is more affected by a visual perturbation than by a cognitive or narrow step placement demand, Gait Posture 42 (2015) 380–385.
[30] J.R. Franz, C.A. Francis, M.S. Allen, S.M. O'Connor, D.G. Thelen, Advanced age brings a greater reliance on visual feedback to maintain balance during walking, Hum. Mov. Sci. 40 (2015) 381–392.