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Effects of visual referencing on backward and forward treadmill walking in VR environments☆

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ABSTRACT

Backward walking is used increasingly as a rehabilitation exercise for stroke and diabetic peripheral neuropathy patients to improve strength and balance. However, it is unclear how visual referencing affects backward and forward walking. In this study, we evaluated spatiotemporal gait characteristics changes due to visual referencing while backward/forward walking. Sixteen healthy young participants were recruited in this study. All participants walked for 2 min with and without visual referencing in the virtual reality environment. While walking backward participants faced the virtual reality screen similar to forward walking, but their treadmill belt direction of movement was reversed. All participants walked at their preferred speed. We found that backward walking with visual reference affected symmetry in step length ($p < 0.05$) and step width ($p < 0.001$). Backward walking increased variability in step length ($p < 0.001$) and COM side excursions ($p < 0.01$) but also increased base of support through increased step width ($p < 0.02$). We also found backward walking with visual reference had significantly increased double support time ($p < 0.001$) and reduced swing time ($p < 0.001$). We also found that backward walking does not predispose to slip and trip risk, thereby, reduced foot contact velocity ($p < 0.0001$) and increased foot clearance ($p < 0.0001$). The findings of this study will help understand the effects of visual reference in backward and forward walking enables clinicians to design patient-centered rehabilitation exercises.

1. Introduction

Backward walking is an emerging rehabilitation exercise tool for the treatment of some orthopedic and neurologic conditions. Backward walking is used in specific athletic training modalities such as tennis for task-specific training [1]. For example, during walking backward one must maintain proper strength and balance [2], and thus backward walking is suggested to affect balance and prevent falls [3]. Backward walking training has been found to improve stability in stroke survivors [3] and is also found to reduce peak plantar pressure among patients with diabetic peripheral neuropathy [4]. Backward walking with alpha-lipoic acid (ALA) is reported to be effective in the treatment of diabetic peripheral neuropathy [4]. In a single subject designed study with a spinal cord injury patient [5], it is reported that walking backward improves functional balance stability such as sit-to-stand. Backward walking with 12–18 bouts of short practice sessions has been reported to improve motor learning skills and has improved physiologic efficiency by reduction of oxygen uptake, heart rate and ratings of perceived exertion (RPE) [6,7]. In addition, backward walking is also associated with increased cardiopulmonary load compared to forward walking [8], and therefore can be used to increase aerobic capacity in athletes who require reduced knee load due to knee injury (ACL injury, patella-femoral pain) [9,10]. Thus *retro*-walking can improve anterior cruciate ligament stability and anterior lateral rotator stability in patients with knee injury. Interestingly walking backward on an inclined plane has been linked with several advantages for the rehabilitation of knee injuries, such as an increase in knee flexion and ankle dorsiflexion [11] and strengthening of quadriceps. *Backward walking in integrated Virtual Reality environments:* Backward walking treadmill therapy is suggested as a critical rehabilitation tool for children with spastic cerebral palsy [12], chronic incomplete spinal cord injury patients [13], among stroke survivors [14,15] and other gait impairments [16]. Backward walking is

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Table 1
Anthropometric information of the participants.

Age (years)	Height (inches)	Weight (kg)
28.2 ± 6.1	65.8 ± 3.8	67.8 ± 14.2

also a biomarker of Parkinson's disease progression [17]. It is difficult to provide a safe backward walking environment in laboratories and clinics. However, treadmill with backward walking functionality along with immersive VR with direction specific optic flow environment could provide ideal therapy to patients. VR augmented rehabilitation have been reported to be effective for stroke patients [18,19]. Stroke patients have been reported to improve in gait symmetry [20]. In addition, from safety perspective, overhead safety harness system along with good control of speed using treadmill self-paced algorithms could prevent falls during backward walking training.

Forward walking versus backward walking: Backward walking is simply not a reversal of forward walking [21] although with same rhythm circuitry [1] (similar cadence), but utilizes different motor plans and specialized control circuits [1,22]. A significant difference is that walking backward relies highly on vestibular and somatosensory information since a complete view of the walking path is lacking when compared with forward walking. In certain rehabilitation conditions, when the impact of heel strike needs to be avoided [9,10], backward walking, which is similar to non-heel-strike gait may be beneficial [1]. Many studies have explored kinematics and kinetics of forward walking and backward walking [23-25]. Both forward and backward walking is reported to have similar hip and knee joint angle patterns, but different ankle angle patterns [26]. Similarly, when considering joint moments, hip and ankle joint moments are found to be similar in forward and backward walking, but different joint moments are produced at knee joint [26]. Some researchers have reported that backward walking utilizes different patterns of phase-dependent modulation of cutaneous reflexes in humans compared to forward walking [27]. In addition, the EMG activity over a gait cycle was found to be higher during walking backward, with a greater level of energy expenditure [23,28,29]. A drastic difference for tibialis anterior (TA), rectus femoris (RF), hamstrings, lateral gastrocnemius (LG), vastus lateralis (VL), and gluteus maximus (GM) [23,24,26,27,30,31] has been reported. Corroborating this, a study by Ivanenko et al. reported that these differences in muscle activity resulted in different spatiotemporal spinal activity maps, with a more intense rostrocaudal banding in backward walking, but similar temporal structure of motor output for both kinds of walking [32]. Undoubtedly, different gait types are related to the different spatiotemporal organization of alpha-motor neuron activity in the spinal circuitry [32] and separate functional networks could be controlling forward and backward walking in humans [33]. Although forward walking is characterized in gait cycles, no information exists on how the backward walking gait cycle can be defined in humans [26]. Besides, knowledge available is limited in how backward walking influences variability in spatial–temporal gait characteristics. On the other hand, vision [34] plays a vital role during walking. Understanding of visual processing while walking in virtual environment setting is limited. Specifically, it is not known how static visual reference can affect fall risk during walking. Some researchers have suggested that lack of external cues provided by vision, deviate walking [35,36], however, how static visual reference affects walking is still not well understood. The purpose of this study is a) to investigate backward walking and characterize "gait cycle" and compare variability among forward and backward walking, b) to investigate how visual reference affects forward/backward gait and if it predisposes participants to high fall risk.

2. Methods

Participants: A total of sixteen healthy participants (8 males, 8 females) participated in this study. The participants anthropometric information is provided in Table 1. Before the experiment each participant signed the informed consent approved by Chapman University IRB. Participants were verbally informed about precautionary measures that would be taken for their safety while walking and the security of their personal information.

Fig. 1. Virtual Reality (VR) display with a red dot creating a forward and backward walking environment, with a treadmill belt capable of moving in two directions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Procedure: All participants performed three walking trials for 2 min in each of the four walking conditions. The four conditions were 1) forward walking with no visual reference, 2) forward walking with a visual reference, 3) backward walking with no visual reference, 4) backward walking with a visual reference. All four conditions were randomized for each participant. The static visual reference was a red dot created in the VR environment (Fig. 1). All participants were asked to continue walking while looking at the static reference colored object and maintain their walking speed. A total of 26 infra-red reflective markers were placed on various body landmarks as per Human Body Model (HBM, Motek Medical, Netherlands) [37]. All participants were harnessed for safety while walking on the treadmill. All participants were asked to walk at their preferred walking speed (for all participant's backward walking speed was slower than that of forward walking). To determine the preferred walking speed, participants were asked to walk on a treadmill at seven equally spaced speeds ranging from 0.67 m/s to 2.01 m/s in ascending order [38]. Participants were asked at every speed if they preferred one over the other speed. The protocol for speed determination was kept the same for forward and backward walking. Once the preferred speed was determined, the self-pace mode of the treadmill was activated. Self-pace mode on the treadmill algorithm was designed to always keep the subject within a prescribed boundary (regarded as 'safe area'). An area of 0.95 m × 1 m in the center of treadmill was programmed as a safe area for the self-paced algorithm. The trajectory position from four infra-red markers in the pelvic region (Right and left ASIS and PSIS) was averaged to mimic the whole-body Center of Mass (COM). This COM position is the central tenet in controlling the treadmill speed to human walking speed. The self-paced algorithm has multiple variables to control for i) speed alterations during walking (0.5 m/s), ii) speed at which treadmill reacts on the COM position of the subjects and return the subject back to the center position within safe area (0.25 m/s). We found that during backward walking participants preferred a speed which was around 50–70% slower than their preferred speed during forward direction walking.

Data Analysis: The marker and forceplate data were utilized to compute all gait parameters such as step length, step width, step

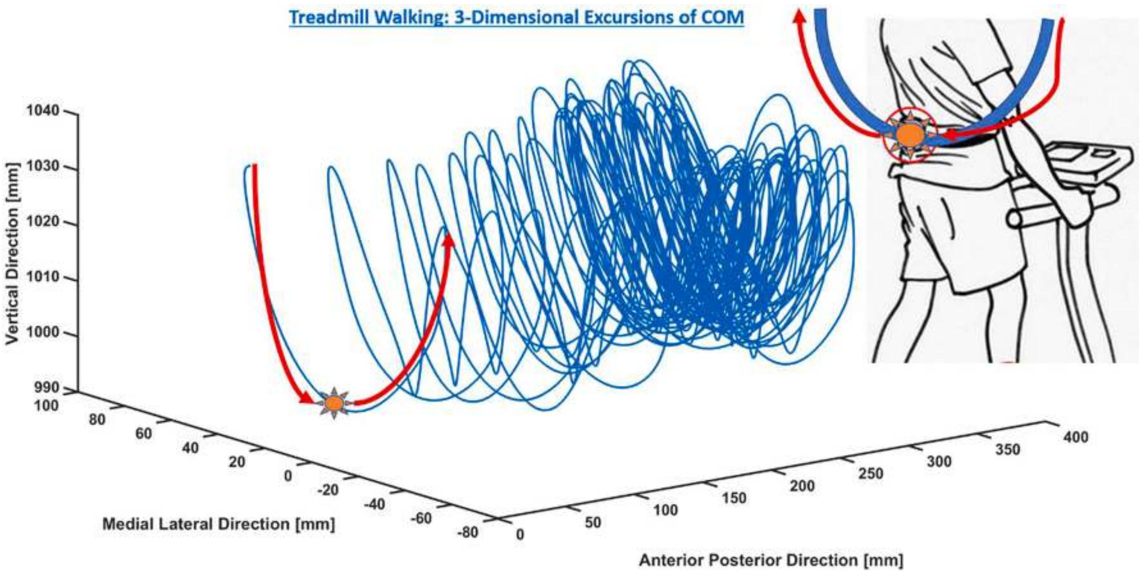


Fig. 2. 3D trajectory excursions of Center of Mass (COM) during forward and backward Treadmill walking.

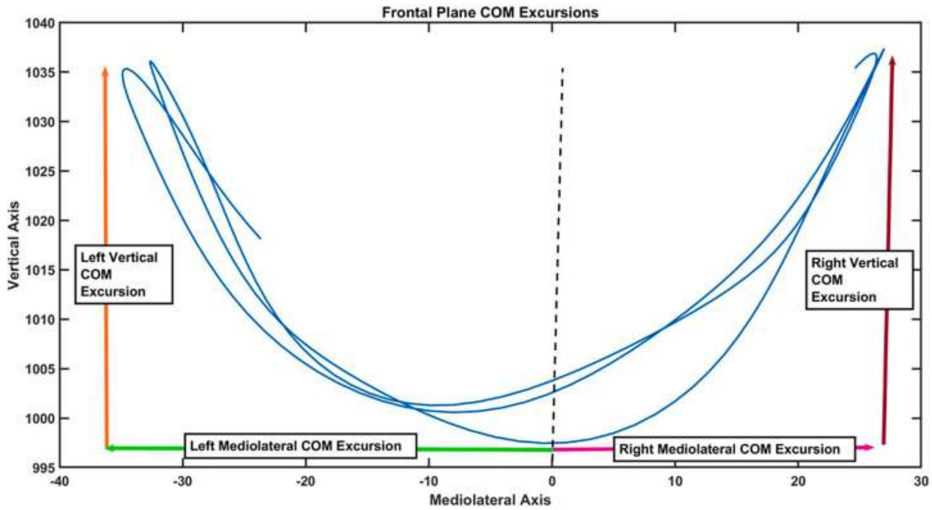


Fig. 3. 3-D frontal plane COM excursions in mediolateral and vertical directions evaluated for both sides for backward and forward walking.

interval, double support time, swing time, gait cycle time, foot contact velocity, foot clearance, Center of Mass (COM) deviation and margin of stability. Step Length and step width symmetry ratio's were obtained from the ratio of the right side to the left side when the right step and consecutively left step were taken (both forward walking and backward walking). Fall risk was evaluated through parameters such as foot clearance height and foot contact velocity. Foot clearance height is the minimum height in mm the foot clears the ground during swing phase, it is either computed using the heel marker or the toe marker whichever is minimum. Foot contact velocity is the velocity of heel marker 100 ms prior to heel contact during forward walking and similarly can be evaluated for backward walking as the velocity of toe marker during toe contact. Gait stability was assessed using the margin of stability [39]. COM velocity was evaluated by differentiating COM position. The extrapolated COM [40] was evaluated as

$$ExtrapolatedCOM = COMPosition + \frac{COMVelocity}{\sqrt{\frac{g}{l}}} \tag{1}$$

where, g is the acceleration due to gravity and l was the mean distance between COM and heel marker (for forward walking) and toe marker (backward walking).

$$MarginofStability = ExtrapolatedCOM - BaseofSupportBoundary \tag{2}$$

The base of support boundary was the farthest reach from the leading foot both in anterior-posterior and medial–lateral directions. The deviations of the center of mass were assessed through excursions of COM as shown in Fig. 2 and Fig. 3.

Symmetry Ratio was computed using the equation below[41].

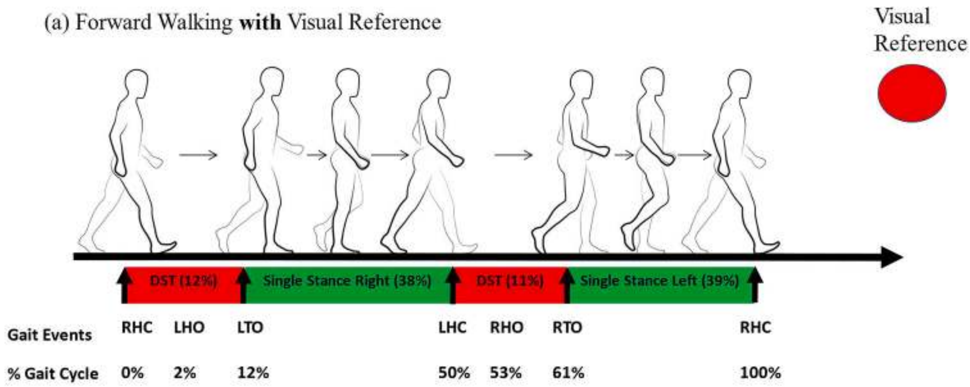
$$SymmetryRatio = \frac{ParameterfromRightFootwhenleading}{Parameterfromcontralaterallimb} \tag{3}$$

Normality was assessed by Kolmogorov-Smirnov testing ($P < 0.05$). A two-way multivariate analysis of variance (MANOVA, $P < 0.05$) was conducted to compare differences in forward/backward walking and visual reference /No visual reference among healthy adults.

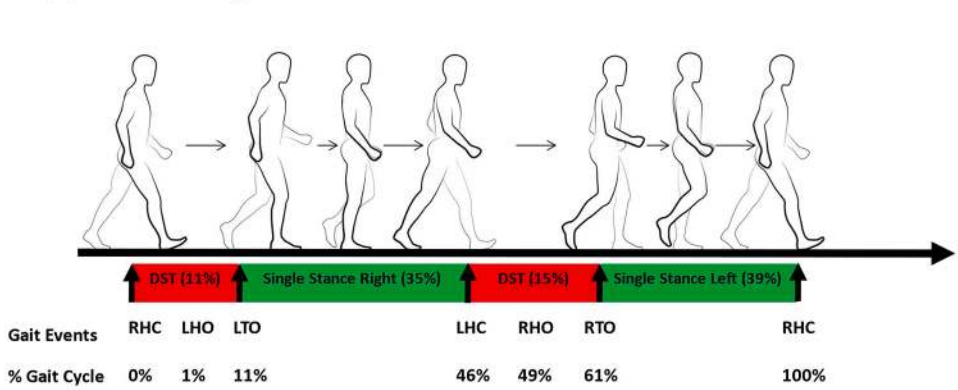
3. Results

Gait Cycles in Forward Walking: For forward walking Gait Cycle (GC) was defined from the Right Heel Contact (RHC) followed by other

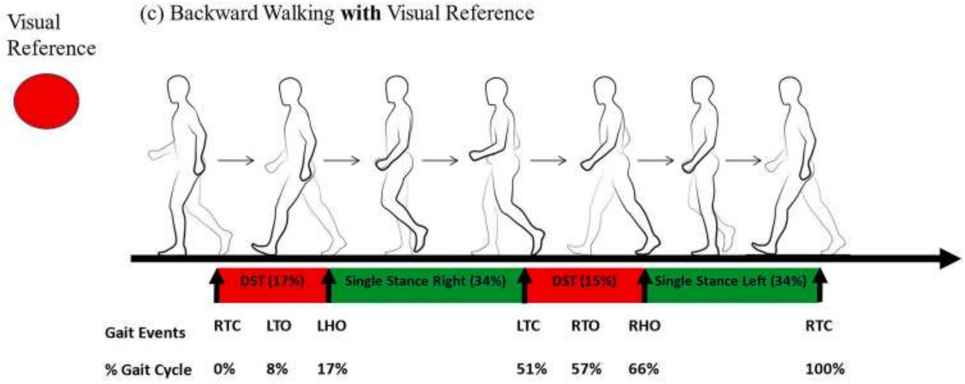
(a) Forward Walking **with** Visual Reference



(b) Forward Walking **without** Visual Reference



(c) Backward Walking **with** Visual Reference



(d) Backward Walking **without** Visual Reference

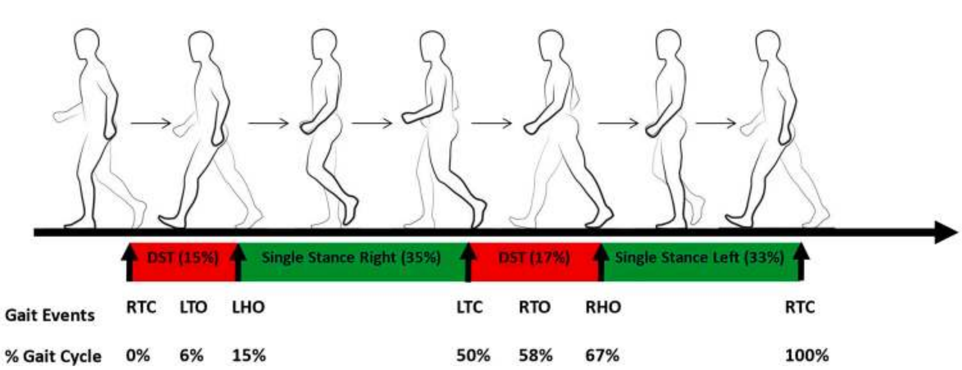


Fig. 4. a) Gait cycle events with single limb and double limb stance times for forward walking with visual referencing b) Gait cycle events with single limb and double limb stance times for forward walking without visual referencing c) Gait cycle events with single limb and double limb stance times for backward walking with visual referencing d) Gait cycle events with single limb and double limb stance times for forward walking without visual referencing. Where the gait events are RHC (Right Heel Contact), LHO (Left Heel Off), LTO (Left Toe Off), LHC (Left Heel Contact), RHO (Right Heel Off), RTO (Right Toe Off), RTC (Right Toe Contact), LTC (Left Toe Contact) and gait phases such as DST (Double Support Time) and Single Stance.

gait events Left Heel Off (LHO), Left Toe Off (LTO), Left Heel Contact (LHC), Right Heel Off (RHO), Right Toe Off (RTO) and the subsequent RHC. When walking forward with a visual reference the Double Support Time (DST) was about 11–12% of gait cycle time and Single Support Time (SST) ranged from 38 to 39% of GC (Fig. 4a). However, when walking forward without visual reference, the SST ranged from 35 to 39% and DST from 11 to 15% (Fig. 4b, Table 2).

Gait Cycles in Backward Walking: For backward walking GC was

Table 2
Gait Variables for backward and forward walking with and without visual reference.

Variables	Backward Walking	Backward Walking with Visual Reference	Forward Walking	Forward Walking with Visual Reference
Step Width Symmetry Ratio	0.983 ± 0.005	0.982 ± 0.006	1.036 ± 0.009	1.024 ± 0.007
Step Length Symmetry Ratio	0.953 ± 0.028	0.890 ± 0.062	1.013 ± 0.009	1.032 ± 0.010
Step Interval [s]	0.850 ± 0.106	0.680 ± 0.073	0.578 ± 0.018	0.587 ± 0.018
Mean Step Length [mm]	322.3 ± 20.5	302.7 ± 25.96	536.6 ± 17.07	542.1 ± 16.70
Mean Step Width [mm]	194.4 ± 19.38	205.3 ± 22.76	159.2 ± 22.85	166.1 ± 23.90
Mean Gait Cycle time [s]	1.497 ± 0.097	1.441 ± 0.075	1.162 ± 0.036	1.169 ± 0.034
Double Support Time (% Gait Cycle)	0.629 ± 0.057	0.704 ± 0.133	0.267 ± 0.012	0.266 ± 0.012
Swing Time (% Gait Cycle)	0.863 ± 0.061	0.743 ± 0.142	0.894 ± 0.026	0.903 ± 0.023
Mean COM Side Excursions [mm]	39.13 ± 4.537	41.77 ± 4.454	27.03 ± 2.988	32.85 ± 3.506
Foot Contact Velocity [mm/s]	0.021 ± 0.001	0.024 ± 0.001	0.050 ± 0.004	0.052 ± 0.005
Foot Clearance [mm]	43.37 ± 1.522	43.68 ± 1.395	41.38 ± 1.387	41.25 ± 1.645
MOS AP [mm]	46.65 ± 3.884	48.81 ± 2.646	29.02 ± 2.753	32.88 ± 2.765
MOS ML [mm]	57.09 ± 4.806	62.15 ± 5.100	38.27 ± 4.480	43.14 ± 4.403
SD Step Length [mm]	31.27 ± 2.706	33.27 ± 3.249	18.54 ± 2.404	15.30 ± 1.598
SD COM Side Excursions [mm]	23.03 ± 2.227	25.45 ± 2.387	16.66 ± 1.526	20.54 ± 1.652

defined from Right Toe Contact (RTC) followed by gait events LTO, LHO, Left Toe Contact (LTC), RTO, RHO and the subsequent RTC. When walking backwards with a visual reference the DST was about 15–17% and SST was about 34% (Fig. 4c). Similarly, we found that when walking backwards without visual reference DST ranged from 15 to 17% and SST ranged 33–35% (Fig. 4d).

The step length symmetry ratio was found to be significantly lower when walking backward compared to forward walking with a visual reference (Fig. 5). It was also found that step width associated symmetry ratios were substantially lower during backward walking compared to forward walking for with and without visual reference trials.

Participants took significantly more time to take steps when walking backward ($p = 0.03$) (Fig. 6a). There was a general trend that participants walked with significantly shorter step lengths compared to forward walking ($p < 0.001$) (Fig. 6b).

Effects of visual reference: We also found that participants when walking backward with static visual reference had significantly wider step widths compared to normal walking in forward direction ($p < 0.02$) (Fig. 6c). The participants took a significantly longer time to complete the gait cycle when walking backward ($p < 0.001$) compared to forward walking (Fig. 6d). It was found that participants had significantly longer double support duration when walking backward with visual reference ($p < 0.001$) (Fig. 6e) compared to forward walking condition. Participants had significantly shorter swing times when walking backward with a visual reference compared to forward walking ($p < 0.001$) (Fig. 6f).

Effects of walking direction: Participants were found to have significantly lower foot contact velocity ($p < 0.0001$) (Fig. 7a) and significantly greater foot clearance ($p < 0.0001$) (Fig. 7b) during backward walking compared to forward walking.

We found that side-to-side excursion was significantly higher for backward walking ($p < 0.01$) compared to forward walking (Fig. 8a). However, the margins of stability were found to be significantly higher in backward walking compared to forward walking ($p < 0.01$) in both anterior-posterior and medial–lateral directions (Fig. 8b and 8c).

We found that variability in step length was significantly higher when walking backward compared to forward walking ($p < 0.001$) (Fig. 9a). However, the lowest variability in COM excursions was found in forward walking without visual reference and backward walking had significantly higher variability in COM excursions ($p < 0.01$) (Fig. 9b).

4. Discussion

Backward walking is an important gait rehabilitation exercise tool for older adults with neuromuscular disorders. It is widely being used in rehabilitation since it involves the coordination of limbs depending mostly upon the coupling of central pattern generators and supervised by brainstem mechanisms [42]. Backward walking involves lower peak vertical ground reaction forces compared to forward walking [10], the loading phase of a gait cycle in backward walking involves concentric contraction of the extensor knee, rather than stressful eccentric contraction in typical forward walking [31]. This makes backward

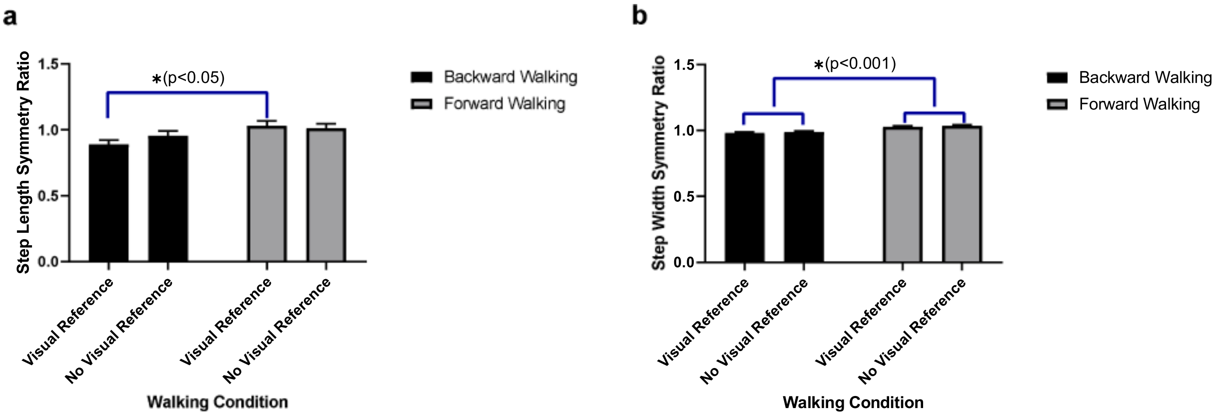


Fig. 5. Symmetry ratio of a) step length and b) step width for forward and backward walking with/without visual reference.

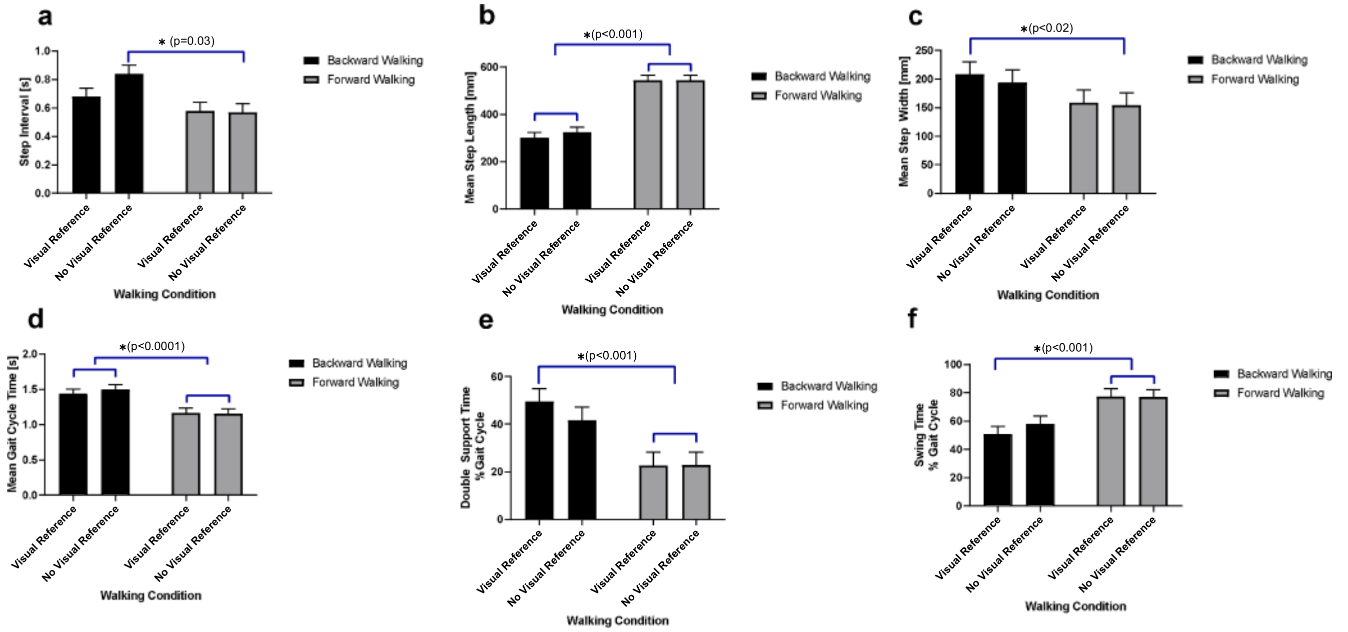


Fig. 6. Gait variables a) Step Interval, b) Step Length, c) Step Width, d) Gait cycle time, e) Double Support time and f) swing time for backward and forward walking.

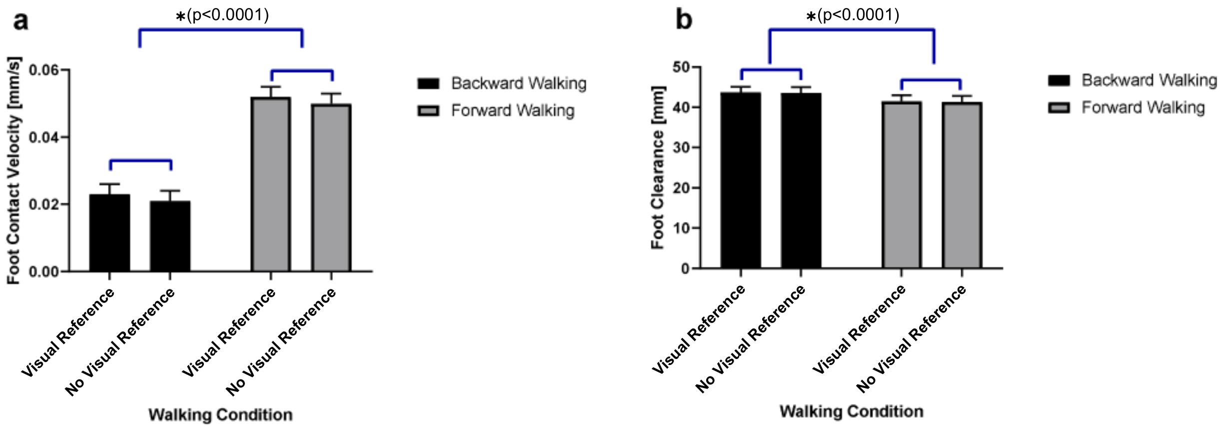


Fig. 7. Gait characteristics related to slip risk a) Foot contact velocity and related to trip risk b) Foot clearance.

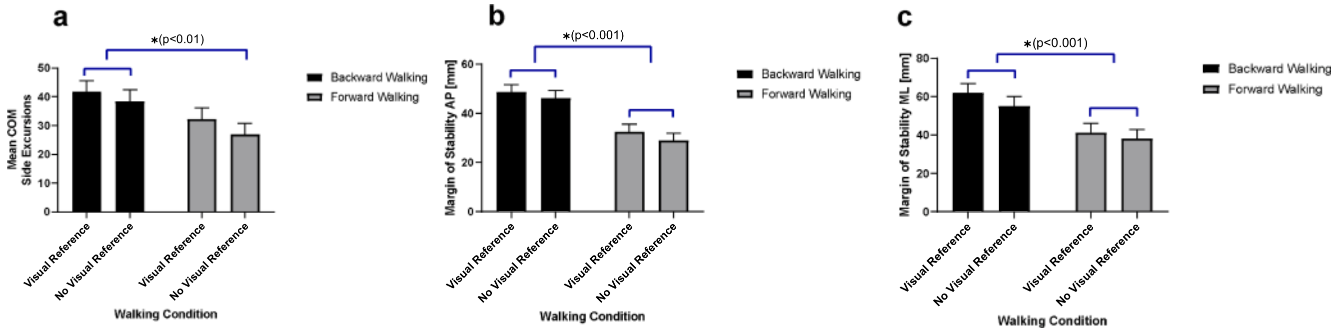


Fig. 8. a) COM excursions on the side and b) margin of stability while walking in a backward and forward direction.

walking suitable exercise for knee injury patients. It is also found to reduce osteoarthritis knee pain [43], improve knee proprioception [44], improve balance [13] and is found to help increase in forward gait speed and stride length compared to forward walking exercises [45]. Since knee joint is most vulnerable to injury in outdoor sports [46,47]. Gait training through backward walking has been found to have improved peak torques produced by quadriceps and hamstrings and thereby improved knee joint stability and knee proprioception [48]. The backward walking has been found earlier to be helpful in improving hamstring flexibility and a low range of motion [49]. Backward walking is beneficial to improve muscle strength, balance, and gait in patients with senile osteoporosis [50]. Considering the visual perspective,

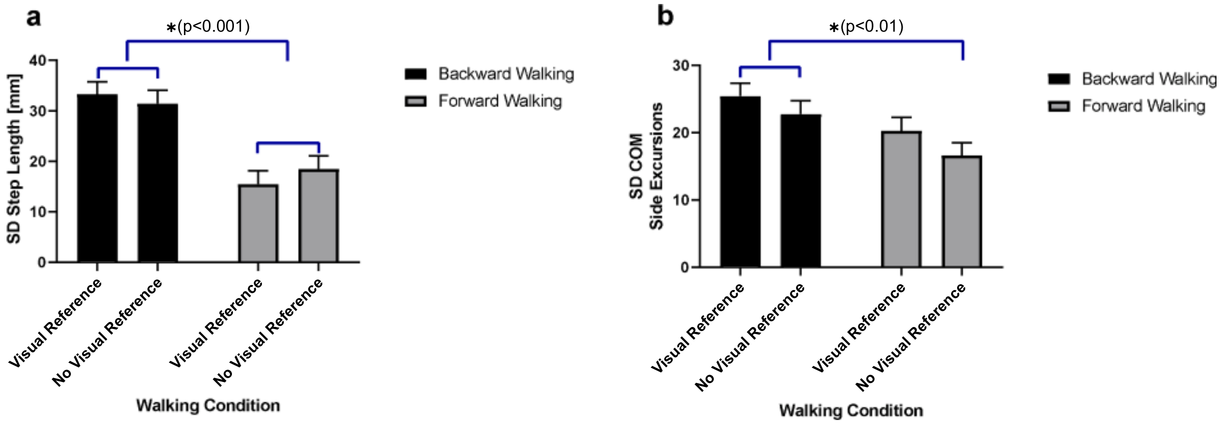


Fig. 9. Variability quantified using standard deviation in a) Step length and b) COM side excursions.

although the dynamic visual cues are present during backward walking [6], optic flow is missing which limits the ability to anticipate obstacles during walking. All the peripheral visual input that provides information about the direction and speed of our movement is biased due to a static visual reference thus limiting capabilities and increased risk compared to forward walking. During walking, one has to organize and adapt the changing information from vision, cutaneous, proprioceptive, and vestibular senses, and then enhance the movement control to maintain dynamic balance [51]. Currently, it is not completely known how backward walking is affected by static visual reference.

We found that step width symmetry is significantly reduced ($p < 0.001$) during backward walking compared to forward walking (Fig. 5b). Particularly we found symmetry in step length was significantly reduced while walking backward with visual reference compared to walking forward ($p < 0.05$) with visual reference (Fig. 5a). Gait symmetry is an important consideration for patients with stroke since symmetry is associated with fall risk [52]. We found that mean step length decreased significantly during walking backward ($p < 0.001$) (Fig. 6b), and mean gait cycle time increased significantly ($p < 0.0001$) compared to forward walking (Fig. 6d). These results are consistent with other researchers who found healthy elderly and young adults significantly reduced their speed while walking backward [53,54]. The elderly have been found to have reduced stride length while walking backward [54]. Body-supported backward walking has been reported to improve walking speed in children with spastic diplegia [55]. We also found that participants produced significantly wider steps with visual reference backward walking compared to forward walking with no visual reference (Fig. 6c). Backward walking has been characterized by reduced gait velocity, stride length, swing time, and an increased double support time but cadence does not change [54]. We found that double support time increased significantly ($p < 0.001$) and swing time decreased significantly ($p < 0.001$) during walking backward with visual reference compared to forward walking (Fig. 6e and f). These may be general mechanisms aimed at maintaining stability with greater double support time implying greater time to acquire proprioceptive information from the feet. Step intervals were found to be significantly more ($p = 0.03$) when walking backward compared with forward walking with no visual reference (Fig. 6a). These characteristics may be stabilizing adaptations due to walking backward. Foot contact velocity was found to be significantly lower when walking backward, thus reducing the slip risk when walking backward compared to normal forward walking (Fig. 7a). We also found that in backward walking participants produced higher foot clearances thus have reduced trip risk (Fig. 7b). We found that COM side (medial–lateral) excursions were significantly higher ($p < 0.01$) when walking backward as shown in Fig. 8a compared to forward walking with no visual reference. Thus, walking backward increases the variability of COM. During backward walking, i) from toe-contact to heel-off, the knee extensor muscles and quadriceps (rectus femoris, vastus lateralis and vastus medialis) get contracted ii)stance phase has decreased descent of the body's center of mass[23,56]. We found that AP and ML margin of stability was significantly higher ($p < 0.001$) for backward walking when compared to forward walking. Thus, although greater deviations of COM were made during walking backward the wider step widths (or larger base of support) kept the gait stable (Fig. 8b and Fig. 8c). We also found variability in COM side excursions ($p < 0.01$) and step length ($p < 0.001$) were significantly higher for backward walking compared to forward walking (Fig. 9a and b). An increase in gait variability has been correlated with increased fall risk [57]. It is also reported variability in gait was more pronounced in older individuals [58] and Parkinson's Disease patients [17,53] compared to younger adults when walking backward. Undoubtedly, backward walking is a difficult task and expected to demand higher coordination [59]. An eight-week forward, backward and sideways gait and step intervention have been reported to have improved gait speed [60,61]. Although VR applications are suggested alternatives for rehabilitation, but may adversely affect human performance due to cybersickness [62]. As per sensory conflict theory, enhancing a specific sensory stimulus may evoke unpleasant sensation due to sensory conflicts among two stimuli [62,63]. Although the VR optic flow was matched with the treadmill speed in this study, a mismatch between visual and vestibular systems can lead to motion sickness [64]. Previously researchers have reported effects of visually stimulated motion sickness on vection and postural stability [65]. However, this has not been reported for gait. Walking is an active exercise and is likely to be affected by cybersickness, as reported by Kiryu and colleagues [66]. However, cybersickness may be eased in a few minutes but is dependent on intensity, duration, usage context and motivation [67]. The conclusions of this study should be considered in the context of its limitations due to cybersickness. Although every attempt was made to match treadmill speed with the virtual reality environment's visual optic flow, the GRAIL system's internal delay was not accounted for in this study.

The findings of this study extend the knowledge available on backward walking, how gait cycles in backward walking are different from those of forward walking. We also found that static visual reference affects both forward and backward gait. Clinicians can include assessment of backward walking in clinical mobility and fall risk assessments. New methods of backward walking assessments with static visual reference will help assess performance in clinical environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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