Advanced technologies to assess motor dysfunction in children with cerebral palsy

Sloot, L.H.

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8 Virtual reality in different modes of treadmill walking

Differences in gait between overground and treadmill walking are suggested to result from imposed treadmill speed and lack of visual flow. To counteract this effect, feedback-controlled treadmills that allow the subject to control the belt speed along with an immersive virtual reality (VR) have recently been developed. We studied the effect of adding a VR during both fixed speed (FS) and self-paced (SP) treadmill walking. Nineteen subjects walked on a dual-belt instrumented treadmill with a simple endless road projected on a 180° circular screen. A main effect of VR was found for hip flexion offset, peak hip extension, peak knee extension moment, knee flexion moment gain and ankle power during push off. A consistent interaction effect between VR and treadmill mode was found for 12 out of 30 parameters, although the differences were small and did not exceed 50% of the within subject stride variance. At FS, the VR seemed to slightly improve the walking pattern towards overground walking, with for example a 6.5mm increase in stride length. At SP, gait became slightly more cautious by adding a VR, with a 9.1mm decrease in stride length. Irrespective of treadmill mode, subjects rated walking with the VR as more similar to overground walking. In the context of clinical gait analysis, the effects of VR are too small to be relevant and are outweighed by the gains of adding a VR, such as a more stimulating experience and possibility of augmenting it by real-time feedback.

LH Sloot, MM van der Krogt & J Harlaar (2014). Effects of adding a virtual reality environment to different modes of treadmill walking. Gait & Posture, 39(3) 939-945.

Introduction

Instrumented treadmills are increasingly applied in gait analysis laboratory settings. Treadmill based gait analysis offers some advantages over overground gait analysis, especially the efficient inclusion of many strides for analysis. However, treadmill walking is known to differ slightly from overground walking, with decreased preferred walking speed, decreased stride length, slightly decreased joint range of motion and small changes in EMG activations [1-5]. Among the suggested explanations for these differences are the absence of a visual flow or the imposed and fixed treadmill walking speed [3,6]. To counteract these effects, feedback-controlled treadmills have been developed that allow the subject to continuously control and inherently select the belt speed, so called self-paced walking, along with an immersive virtual reality environment.

The use of virtual reality (VR) environments during treadmill walking is becoming increasingly popular in the area of rehabilitation medicine, since a VR provides an engaging environment with the suggestion of a real-life situation. This is likely to induce a real life sensation and improve activity adherence in the case of training. Such an environment also offers the possibility of real-time feedback, such as visual cues [7]. It has been shown that VR-based treadmill training improved walking speed and community ambulation more compared to training without a VR in patients with stroke [8]. Combining a VR environment with self-paced treadmill walking would allow for training in an even more realistic real-life situation, including training of real-life tasks like crossing roads while measuring variation in walking speed and fatigue. In addition, manipulation of optical flow can be included in rehabilitation training, to unconsciously motivate patients to increase their walking speed [9,10], although this effect may not be lasting [11].

Several studies have already examined the effect of a VR environment on gait. Surprisingly, addition of a VR environment does not normalize the comfortable walking speed to overground values, but instead lowers the stride length even further, with increased step width [12,13]. In addition, subjects show increased walking speed variability and step width variability [10,13,14]. Together, these findings are interpreted as a sign of a more conservative or cautious gait, perhaps induced by instability due to the VR environment [12,13]. This instability may be caused by the perceptual mismatch between optical flow and walking speed, since it has been found that treadmill walking slowed down the perceived optic flow relative to the walking speed [15,16]. Alternatively, it may be related to the fidelity of the VR environments, indicating that the frequently used corridors and hallways do not represent a realistic surrounding or optical flow pattern. In contrast to these findings, an increase in walking speed and stride cadence during walking in a VR environment has also been found [17]. This study combined a VR environment, a head mounted device instead of a projection screen, as well as a self-paced treadmill. It remains undetermined if the conflicting results of walking in a VR environment are caused by the different concepts to create VR or the different treadmill modes.

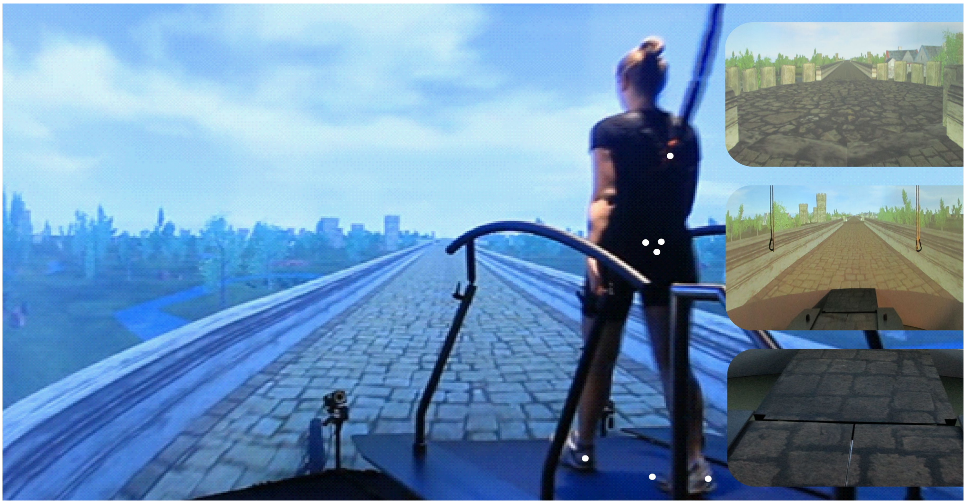

Fig 8-1. GRAIL experimental set-up, consisting of a dual-belt treadmill, 180° VR environment with ground projection (see inset) and optoelectronic motion analysis system. The speed-matched scene consisted of a simple road with a changing rural landscape.

In our previous study, we examined the difference between self-paced and fixed speed treadmill walking, both within the virtual reality environment. No clinically relevant differences were found between the gait patterns, for all spatiotemporal, kinematic and kinetic parameters, but self-paced walking resulted in increased long-term walking speed variability [18]. However, it is still unknown what the effect of the virtual reality environment was within each treadmill mode. Therefore, in this study we investigated the main effect of a VR environment and the interaction effect of VR and treadmill mode, *i.e.* fixed speed (FS) versus self-paced (SP) walking, on spatiotemporal, kinematic and kinetic gait parameters.

Methods

Nineteen healthy subjects (age: 29.2±5.0 yrs.; BMI: 24.2±3.3; 12 male) walked on a split-belt instrumented treadmill in a virtual environment, of which the optical flow was continuously matched to the walking speed (Fig. 8-1; GRAIL, Motek Medical BV, the Netherlands). The experimental conditions were from the same sessions as our previous study [18]. An endless, straight and paved road within a rural landscape was projected on the 180° circular screen and on the ground. Force sensors underneath each belt (50x200cm) recorded the ground reaction forces and moments. 3D kinematics of the lower body was tracked using a passive marker motion capture system (Vicon, Oxford, UK). Force and motion data were sampled at 120Hz and used to calculate joint kinematics and kinetics based on the Human Body Model (HBM; Motek Medical BV) [19]. Subjects signed informed consent and the protocol was in accordance with the procedures of the local ethics committee.

After at least 6 min of habitation to both treadmill modes with VR, subjects walked for 3 min in SP mode to determine the preferred walking speed used to set the speed in the FS trials. Then, four conditions were measured in random order: walking in SP mode both with and without the VR environment as well as walking in FS mode both with and without the VR. Data of the trials with VR was previously presented, *i.e.* SP_p and speed-matched FS [18]. All trials lasted 3 min, of which data was recorded during the last minute. After each trial, subjects were asked to subjectively rate the resemblance to normal overground walking, overground preferred walking speed and overground fatiguing, on a scale from 1 (totally different) to 10 (fully identical). During SP walking, the belt speed was controlled based on the position and speed of the subject, *i.e.* the SP_p algorithm, which was selected because this algorithm appeared the most comfortable SP mode in our previous study [18]. Position was determined by the average of four pelvic markers filtered at 2Hz. Belt speed was adjusted 30 times per second, using a 6 kW motor per belt. Each actual belt speed change was proportional to the distance between the subject and the middle of the belt and also to the speed difference of the subject and belt, the gain of which was a function of the distance to the middle of the belt.

The recorded data from the force sensors and motion capture were low-pass filtered at 6 Hz. Sagittal kinematics and kinetics of the hip, knee and ankle were calculated using HBM and time normalized to 0-100% of the gait cycle. Strides with foot placement on both belts were excluded from further analyses. From the foot marker data we calculated stride length and time, walking speed, step width and stance percentage per stride. The kinematic curves were quantified by their mean value ('offset') and offset-corrected RMS ('magnitude'), while the kinetic curves were quantified by the ratio of area under the curves ('gain') and the gain-corrected RMS. Furthermore, conventional clinically relevant features of the gait pattern were calculated, based on the kinematic parameters as used in the Gillette Gait Index [20], as well as a set of relevant kinetic parameters (see Table 8-2).

A two-factor repeated measures ANOVA was used to examine the effect of walking with or without a VR environment (VR-condition) for the different treadmill modes (SP-condition) on walking speed and subjective ratings. On the remaining spatiotemporal, kinematic and kinetic parameters, linear generalized estimating equation (GEE) analyses were performed, for this analysis allows for repeated measures with time-dependent covariates and thus can correct for walking speed differences between and within subjects, *i.e.* between conditions, without the need for assumptions of normal distribution or homogeneity of variance. The working correlation structure was set at exchangeable and based on robust estimation (SPSS, v20.0). To assess the main effects at average walking speed, the average walking speed over all conditions (1.35 m/s) was subtracted from the individual walking speed values. Since addition of an interaction term into the model drastically alters the interpretation of the coefficients, two different models were used. First, the main effect of VR was determined following this model including the categorical predictor variables VR and SP:

$$\text{Outcome} = b_0 + b_1(\text{VR}) + b_2(\text{SP}) + b_4(\text{speed}) + \ldots$$
$$b_{5,VR}(\text{VRxspeed}) + b_{6,SP}(\text{SPxspeed}) + \varepsilon \quad (8.1)$$

with b_0 the regression coefficient representing the intercept value (*i.e.* the value at average walking speed) of the outcome measure during SP walking with VR; b_1 the average difference in outcome measure at average walking speed between walking with and without the VR (main effect of VR); b_2 the average difference between walking at SP versus at FS (main effect of SP); b_4 the average slope of the outcome measure versus speed, *i.e.* the main correction for walking speed; b_5 and b_6 the difference in slope between groups, *i.e.* correction for interaction effects between the VR and SP conditions and speed; and ε the residual error term. The terms correcting for confounders ($b_{4\text{-}6}$) were only included if inclusion resulted in more than 10% change in the VR-coefficient (b_4) or if one of the interaction terms was significant ($b_{5,VR}$, $b_{6,SP}$). The main effect of VR was considered significant if $p>0.05$, with the coefficient b_1 giving the size of the effect of VR.

Next, the interaction effect of VR and treadmill mode was determined using a model which included the interaction term between VR and SP:

$$\text{Outcome} = b_0 + b_1(\text{VR}) + b_2(\text{SP}) + b_3(\text{VRxSP}) + b_4(\text{speed}) + \ldots$$
$$b_{5,VR}(\text{VRxspeed}) + b_{6,SP}(\text{SPxspeed}) + \varepsilon \quad (8.2)$$

now, b_1 is the average difference in outcome measure at average walking speed between walking with and without the VR during SP walking; b_2 the difference in value between walking at SP versus at FS with VR; and b_3 the difference in value between the groups, *i.e.* additional effect of walking at FS without a VR environment (interaction effect). The speed correction terms remained the same and were included under the same conditions. For both models, main speed correction was included except for 3 parameters, *i.e.* knee flexion at initial contact, ankle flexion moment RMSE and ankle power at push off, in which cases exclusion of speed correction did not affected the outcomes. From the estimated means resulting from the models, the size of the effect of VR during SP walking as well as during FS walking was determined. These effect sizes were compared with the average intra-individual stride variance of the parameters measured at FS walking. The gait pattern was not directly compared between FS and SP treadmill walking since this comparison is elaborately described elsewhere [18].

Results

Walking with VR was scored as better resembling normal overground walking than walking without VR, *i.e.* 6.8 versus 6.0 (see Table 8-1). Averaged over the three subjective questions, resemblance to overground walking, preferred walking speed and fatiguing, VR walking was rated as more similar to normal overground walking. No interaction effect was found. Walking speed was increased during SP walking com-

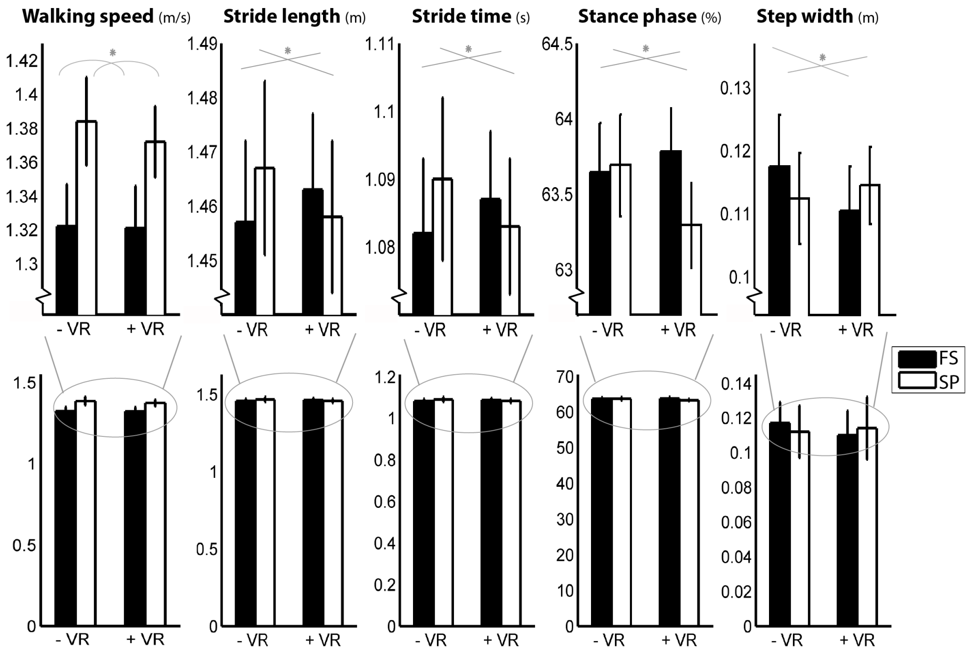

Fig 8-2. Spatiotemporal parameters with inset enlargements compared between the four conditions: without VR versus with VR for both treadmill modes, for FS in black and SP in white. The measured average and standard error (error bar) are given for walking speed and the effect found with the ANOVA is indicted (p<0.05). For the other measures, the speed corrected estimates from the GEE model are given with the standard error.

pared to FS walking by 0.06 m/s (p<0.01), even though FS was set to the preferred walking speed based on a baseline SP-trial (Fig. 8-2). An effect of VR was found for 5 out of 30 parameters tested. With the VR, hip flexion offset was increased with 0.9% to without VR (p<0.001), while max. hip extension decreased with 4.2% (p<0.001), knee flexion moment gain increased with 1.1% (p=0.03), max. knee extension moment increased with 1.1% (p=0.02) and ankle power during push off increased with 5.6% (p<0.01).

An interaction effect between VR and treadmill mode was found for all spatiotemporal parameters in the GEE (all p<0.01; Fig. 8-2, Table 8-2). At FS, stride length increased 6.5 mm with VR compared to without VR, while at SP stride length decreased 9.1 mm with VR (p=0.003). Similarly, at FS stride time increased 5 ms with VR, stance time increased 0.13% and step width decreased 6.5 mm, while at SP stride time was 7 ms shorter, stance time decreased 0.39% and step width increased 2.6 mm (all p<0.02). The differences due to the VR environment were all within 50% of the average stride variance measured during FS walking.

The kinematic parameters showed an interaction effect for 6 out of 13 parameters (Fig. 8-3, Table 8-2). At FS, knee flexion angle increased 0.058° with VR (RMS-value; p<0.01), range of hip flexion increased 0.25° (p=0.03), knee flexion at initial contact decreased 0.20° (p<0.01), time to peak knee flexion during swing was 0.10% delayed (p<0.01) and range of knee flexion increased 0.24° (p<0.01). At SP, knee flexion angle

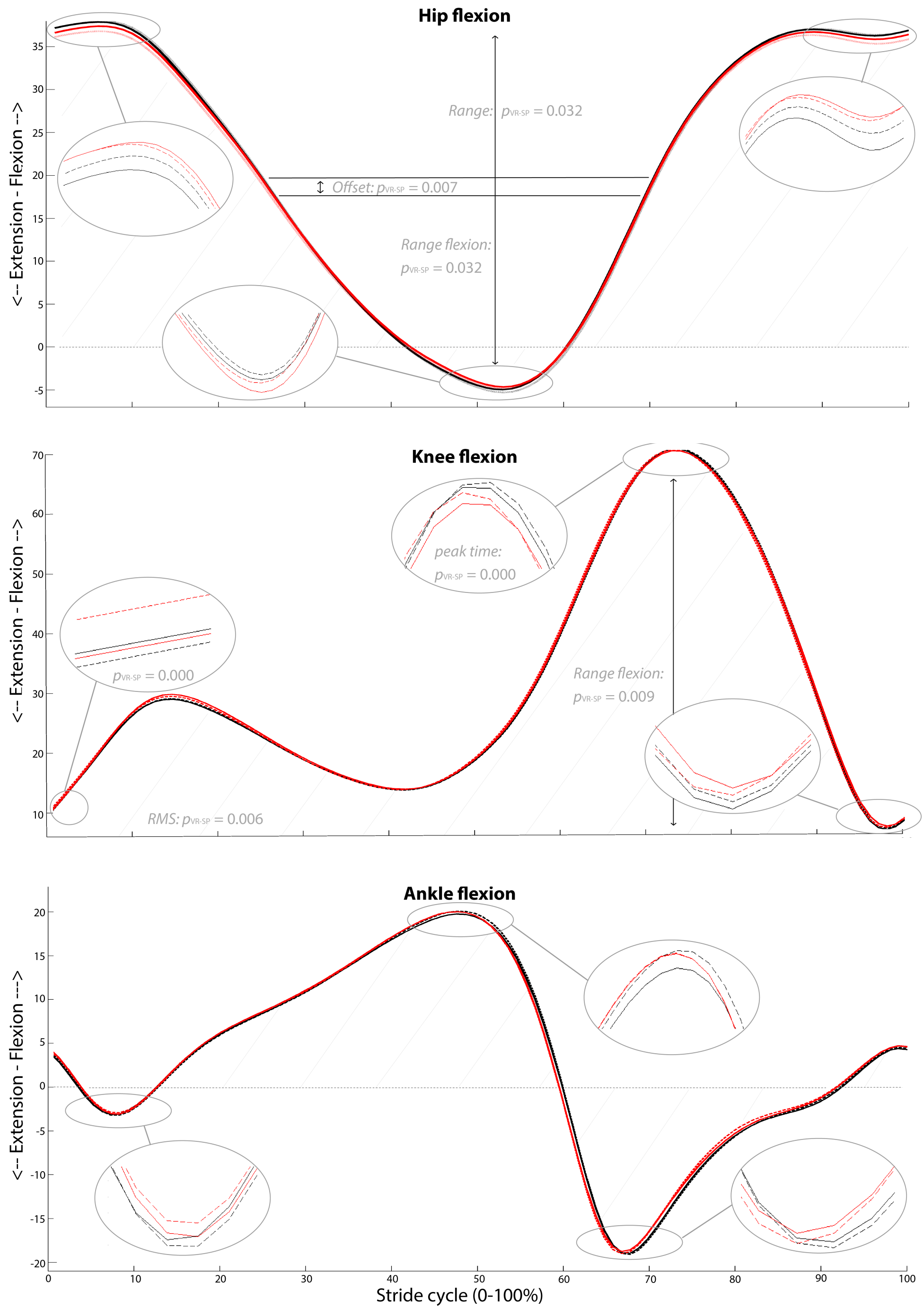

Fig 8-3. Time-normalized joint kinematics averaged over subjects without speed correction for the four conditions. Significant differences are indicated, e.g. hip flexion range and offset, knee RMS, range of peak knee flexion in swing and knee flexion at initial contact.

decreased 0.09°, range of hip flexion decreased 0.35°, knee flexion at initial contact increased 0.40°, time to peak knee flexion during swing was 0.18% early and range of knee flexion increased 0.40°. In addition, at FS mean hip flexion angle increased 0.31° with VR, while at SP it increased with 0.08° (offset; p=0.007). These differences of VR were all within 40% of the stride variance measured during FS walking.

Two out of the 13 kinetic parameters demonstrated an interaction effect (Table 8-2). FS walking with the VR cost 3.2 mW (3%) less exerted hip power and 3.3 mW (2%) less absorbed knee power (both p=0.04). At SP the VR resulted in 2.7 mW (2%) and 10.4 mW (5%) more hip and knee power during push off. These effects were within 25% of between stride variance.

Discussion

Irrespective of the treadmill mode, subjects perceived walking within the VR environment as slightly more similar to normal overground walking, than without VR. The VR was found to increase hip flexion offset, knee flexion moment, peak knee extension moment, ankle power push off and decrease maximum hip extension. Further analysis showed consistent interaction effects of VR and treadmill mode.

The effect of VR on gait was fairly small in both treadmill modes, since it never exceeded 50% of the within subject between stride variance measured during FS walking. Differences in spatiotemporal parameters were in the order of millimeters and milliseconds and the range of motion was changed less than 0.5°. Therefore, we suggest that these differences in gait parameters are too small to be clinically relevant. Although small, VR and treadmill mode interactions were consistently found, for 12 out of the 30 parameters, spread over all three outcome domains, *i.e.* spatiotemporal, kinematic and kinetic parameters. At FS the gait pattern improved by the addition of VR, likely better resembling overground walking. Stride length as well as stride time became longer with VR, with reduced step width, increased hip and knee range of motion in the sagittal plane, increased knee extension at initial contact, less generated hip power and less absorbed knee power during push off; all clinically considered as positive gait features. The only exception was stance percentage, which was increased with VR. In contrast, at SP the gait pattern seemed to become more cautious by the addition of VR, *i.e.* a shorter stride length and stride time, increased step width and reduced hip and knee range of motion. In addition, more knee power was absorbed and more hip power generated during push-off. Since the VR environment and the scene were fixed between conditions, the interaction seemed related to the control mode of the treadmill speed. We suggest that by focusing on the VR scene on the screen, subjects were less aware of their exact position on the treadmill. Knowing that the belt has limited length, subjects might become more cautious when walking in the VR environment. This adaptation is most likely to happen unconsciously, because it was not reflected in the subjective scores. At FS, the positive effect of the VR, *i.e.* a stronger experience of a real-life environment, may be more dominant, resulting in an improved gait pattern. It should be noted that while the differences in gait parameters were too small to be clinically relevant, the subjective scores show that subjects preferred walking with VR.

The interaction effect we found, although small, is in contrast with what we expected from literature: studies at FS report a more cautious gait due to a VR environment [12-14], while at SP, a similar or even improved gait pattern was found with VR [17]. In addition, Hollman *et al.* reported large differences in effect size, *i.e.* around 5 cm in stride length and 1 cm in stride width [13], while effects in the order of millimeters were found in our study. Since the speed of the optical flow was synchronized with the treadmill speed in all studies, the contrasting effects might be due to a difference in fidelity of the VR scene, the field of view resulting from the VR environment as well as treadmill dimensions. In the studies of Hollman *et al.*, subjects walked on a relative small treadmill with a concave screen right in from of them, resulting in a 160° field of view [12,13]. The scene consisted of a corridor with colored, vertical stripes on the wall. Another study projected a 3D endless virtual corridor on a flat screen three meters in front of the subject, creating a field of view of 52°, for which subjects had to wear red-blue stereo glasses [14]. In a SP study, a head mounted device was used, resulting in a 60° field of view, projecting a local hallway including an motion-coupled avatar [17]. In our study, a 180° field of view was created by a circular screen standing a few meters in front of the subject with additional ground projection. Subjects did not have to wear special glasses or head mounted devices, while walking in a changing outdoor scene on a relative large walking surface of the treadmill. So, the content and fidelity of the VR scene, field-of view, VR environment set-up as well as the treadmill walking surface seem to differ substantially between these studies. This suggests that the effect of a VR might depend on the specific VR environment set-up.

Although FS was set to an average of a prior self-paced walking trial, fixed speed was decreased by 4.1% compared to SP walking. This indicates that some learning effect might have taken place between the baseline SP trial and the later SP trials used to test for VR effects, that may affect the comparison between gait patterns of FS and SP treadmill walking. However, we corrected gait parameters for walking speed. Therefore, it seems unlikely that the effects of VR we found were due to these habituation effects. Another study limitation is that statistical tests were performed without correction for multiple comparisons. Thus, with the number of tests performed, it

Table 8-1. Subjectively rated resemblance to over ground walking

	Main effect VR			**Interaction effect**	
Resemblance to…	+ VR	- VR		+ VR	- VR
Q1: overground walking	6.8±1.2	6.0±1.4**	+ SP	6.7±1.2	5.9±1.5
			− SP	6.9±1.1	6.1±1.3
Q2: preferred walking speed	7.2±1.5	7.0±1.3	+ SP	7.3±1.3	7.1±1.3
			− SP	7.1±1.6	6.8±1.1
Q3: fatiguing of overground walking	7.3±1.1	7.1±1.3	+ SP	7.6±1.1	7.1±1.3
			− SP	7.1±1.3	7.1±1.2
Average of questions	7.1±1.3	6.7±1.4*	+ SP	7.2±1.2	6.7±1.5
			− SP	7.0±1.4	6.7±1.3

Significant differences are indicated, with $^{*}p<0.05$ and $^{**}p<0.01$.

Table 8-2. Interaction effects between VR and treadmill mode

	FS		SP		Interaction		
	– VR	+ VR	– VR	+ VR	*p*	VR_{FS}	VR_{SP}
Spatio-temporal							
Walking speed (m/s)	1.321± 0.025	1.321± 0.025	1.387± 0.026	1.370± 0.020			
Stride length (m)	1.457± 0.013	1.463± 0.012	1.467± 0.014	1.458± 0.012	0.003	0.007	-0.009
Stride time (s)	1.082± 0.010	1.087± 0.009	1.090± 0.011	1.083± 0.009	0.004	0.005	-0.007
Stance percentage (%)	63.62± 0.312	63.75± 0.282	63.67± 0.329	63.27± 0.272	0.017	0.129	-0.391
Step width (m)	0.117± 0.008	0.110± 0.007	0.112± 0.007	0.114± 0.006	0.000	-0.007	0.003
Kinematics							
Hip flex RMS (°)	15.59± 0.26	15.69± 0.29	15.73± 0.28	15.64± 0.26			
Hip flex offset (°)	19.53± 1.14	19.86± 1.13	19.74± 1.14	19.82± 1.12	0.007	0.330	0.068
Hip ext max (°)	-5.17± 1.32	-4.96± 1.31	-5.10± 1.32	-4.87± 1.30			
Hip flex range (°)	43.28± 0.85	43.53± 0.92	43.68± 0.87	43.33± 0.81	0.032	0.246	-0.352
Knee flex RMS (°)	19.10± 0.30	19.19± 0.30	19.11± 0.32	19.02± 0.31	0.006	0.085	-0.092
Knee flex offset (°)	30.06± 0.47	30.05± 0.48	30.25± 0.45	30.15± 0.46			
Knee flex range (°)	63.56± 0.86	63.80± 0.88	63.62± 0.92	63.22± 0.87	0.009	0.243	-0.398
Knee flex IC (°)	9.46± 0.77	9.26± 0.77	9.42± 0.79	9.82± 0.78	0.000	-0.203	0.400
Knee ext max time (%)	73.33± 0.21	73.43± 0.22	73.46± 0.22	73.29± 0.21	0.000	0.101	-0.175
Ankle flex RMS (°)	10.64± 0.26	10.78± 0.25	10.67± 0.25	10.62± 0.24			
Ankle flex offset (°)	3.27± 0.54	3.33± 0.52	3.30± 0.54	3.37± 0.53			
Ankle ext max stance (°)	20.26± 0.59	20.62± 0.65	20.53± 0.64	20.51± 0.63			
Ankle ext max swing (°)	4.77± 0.65	4.90± 0.62	4.79± 0.65	4.86± 0.63			
Kinetics							
Hip M RMS (Nm/kg)	0.62± 0.02	0.62± 0.02	0.64± 0.02	0.63± 0.02			
Hip M gain (Nm/kg)	1.02± 0.02	1.02± 0.02	1.03± 0.02	1.02± 0.02			
Hip M max (Nm/kg)	-1.02± 0.04	-1.03± 0.04	-1.09± 0.04	-1.08± 0.04			
Hip M range (Nm/kg)	2.49± 0.09	2.49± 0.09	2.52± 0.09	2.50± 0.08			
Hip P push off (W/kg)	0.13± 0.01	0.12± 0.01	0.13± 0.01	0.13± 0.01	0.036	-0.003	0.003
Knee M RMS (Nm/kg)	0.27± 0.01	0.26± 0.01	0.26± 0.01	0.26± 0.01			
Knee M gain (Nm/kg)	1.01± 0.02	1.02± 0.02	1.01± 0.02	1.02± 0.02			
Knee M_{ext} max (Nm/kg)	0.66± 0.03	0.67± 0.02	0.66± 0.03	0.67± 0.02			
Knee P push off (W/kg)	-0.21± 0.01	-0.20± 0.01	-0.20± 0.01	-0.22± 0.01	0.036	-0.003	0.010
Ankle M RMS (Nm/kg)	0.72± 0.04	0.67± 0.03	0.63± 0.04	0.62± 0.03			
Ankle M gain (Nm/kg)	0.99± 0.01	1.00± 0.01	1.01± 0.01	1.01± 0.01			
Ankle M_{ext} max (Nm/kg)	1.46± 0.05	1.47± 0.05	1.47± 0.05	1.48± 0.05			
Ankle P push off (W/kg)	0.16± 0.01	0.17± 0.01	0.17± 0.01	0.17± 0.01			

Note that speed-corrected estimates (mean and standard error) from the GEE analysis are shown. For the significant interaction effects, the *p*-values and effect sizes of VR at FS and at SP walking, respectively, with a positive effect size indicating an increase compared to walking without VR. With flex flexion, ext extension, IC initial contact, M moment, and P power.

might be that some coincidentally significant differences were found. However, since the interaction effects were consistent in direction and were found in multiple parameters of each outcome domain, *i.e.* in both spatiotemporal, kinematic and kinetic parameters, it is unlikely that these interaction effects were just coincidentally significant.

Conclusion

This study compared the effect of VR during both FS and SP treadmill walking. We mainly found an interaction effect of VR and treadmill mode: at FS walking a VR led to a slightly improved gait pattern, while at SP gait became slightly more cautious with VR. The inconsistency with literature suggests that the effect of a VR depends on the specific VR environment set-up. Nevertheless, the interaction effects we found were too small to be clinically relevant and subjects rated walking with the VR as more similar to overground walking. So it seems that slight drawbacks are outweighed by the gains of using a VR, such as a more real-life and motivating environment and the possibility of augmenting it by providing real-time feedback.

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