Advanced technologies to assess motor dysfunction in children with cerebral palsy

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2016

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Sloot, L. H. (2016). *Advanced technologies to assess motor dysfunction in children with cerebral palsy*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

9 Effect of self-paced walking and virtual reality in CP

While feedback-controlled treadmills with a virtual reality could potentially offer advantages for clinical gait analysis and training, the effect of self-paced walking and the virtual environment on the gait pattern of children and different patient groups remains unknown. This study examined the effect of self-paced (SP) versus fixed speed (FS) walking and of walking with and without a virtual reality (VR) in 11 typically developing (TD) children and nine children with cerebral palsy (CP). We found that subjects walked in SP mode with twice as much between-stride walking speed variability ($p<0.01$), fluctuating over multiple strides. There was no main effect of SP on kinematics or kinetics, but small interaction effects between SP and group (TD versus CP) were found for five out of 33 parameters. This suggests that children with CP might need more time to familiarize to SP walking, however, these differences were generally too small to be clinically relevant. The VR environment did not affect the kinematic or kinetic parameters, but walking with VR was rated as more similar to overground walking by both groups ($p=0.02$). The results of this study indicate that both SP and FS walking, with and without VR, can be used interchangeably for treadmill-based clinical gait analysis in children with and without CP.

LH Sloot, J Harlaar & MM van der Krogt (2015). Self-paced versus fixed speed walking and the effect of virtual reality in children with cerebral palsy. Gait & posture 42(4), 498-504

Introduction

In clinical gait analysis, instrumented treadmills are increasingly used to measure constitutive strides. To imitate overground walking, feedback-controlled treadmills with immersive virtual reality (VR) environments have been introduced [1,2]. These treadmills allow for self-paced (SP) walking as an alternative to the traditional imposed fixed speed (FS) and provide a visual flow coupled to the subject's walking speed. Other potential clinical advantages include the possibility of measuring fatigue and stride variability, the lack of a need to pre-determine the preferred fixed walking speed, and a motivational environment that can also be used to provide visual feedback to patients. For interpretation of treadmill-based clinical gait analysis, it is however important to know the effects of SP walking and of the use of VR.

Previously, it was found that SP walking resulted in increased long-term walking speed variability in able-bodied adults [3], suggesting that it allowed for more stride variability as seen during normal overground walking [4,5]. However, there were no clinically relevant differences between SP and FS walking [3,6]. The effect of SP has only be examined in transtibial amputee patients, and while it was found that they walked faster in SP mode, there was no effect found on kinematics or kinetics when controlling for this speed difference [6]. Allowing subjects to vary their walking speed could potentially lead to a more natural walking pattern. In addition, it would allow for determination of long-term stride interval correlations, which have been found to alter with age and pathology, and are suggested to relate to changes in the central nervous system control [7-9].

Contradictory effects of VR have been reported for treadmill walking, showing either a more cautious gait, with increased step width, decreased stride length and increased walking speed variability [10-13], or a more confident gait with increased walking speed [14]. The different findings could result from the fidelity of the VR environment or the treadmill speed mode (*i.e.* FS or SP) that was used. A recent study showed that the effect of VR was dependent on the treadmill speed mode, with the addition of VR resulting in a more cautious gait in SP and a more confident gait pattern in FS, although these differences were small [15]. Furthermore, subjects perceived walking with VR as more similar to overground walking [15]. As VR environments and SP walking are becoming applied in the area of rehabilitation medicine for gait analysis and training, their effect on the gait pattern of children and different patient groups should be examined.

Therefore, the aim of this study was to examine the effect of treadmill speed mode (*i.e.* SP versus FS walking) and a VR environment on spatiotemporal, kinematic and kinetic gait parameters in typically developing children (TD) and children with spastic cerebral palsy (CP). The presented study is complementary to a previous study, comparing SP walking with VR to conventional overground walking in the same participants [16].

Methods

Nine children with spastic CP (5 female; 11.6±2.1 (8-14) yrs, BMI 18.3±2.9 kg/m^2, GMFCS I or II) and 11 TD children with similar characteristics (4 female; 10.6±2.2 (8-15) yrs, BMI 16.4±1.6 kg/m^2) participated in this study (for more details see van der Krogt *et al.* [16]). Children with CP were included if they could walk independently without walking aids for at least 5 min on end and 30 min in total, had not received multilevel surgery, selective dorsal rhizotomy or baclofen treatment within the last year or botulin toxin A treatment within the last 16 weeks and were classified as level I or II on the gross motor function classification scale (GMFCS [17]). All parents and children above 11 years provided written informed consent. The protocol was approved by the local medical ethics committee.

Design and materials

Subjects walked on a dual-belt instrumented treadmill (R-Mill, Forcelink, The Netherlands) placed in a speed-matched virtual environment, consisting of a 180° projection of an endless, straight forest road and scenery (GRAIL, Motek medical, The Netherlands) [16]. In SP mode the speed of the belt was real-time adjusted based on the subject's position on the belt and velocity to match the subject's walking speed [3]. Subjects walked on their own low-model, flat sole shoes, with orthoses or insoles if used on a regular basis (three and one subjects with CP respectively). They were instructed to walk in the mediolateral middle of the treadmill and wore a safety harness.

After 6 to 10 min to familiarize to SP and FS treadmill walking, a baseline SP trial was performed to determine the preferred walking speed at which FS was set. Next, four trials were randomly performed: walking at FS and SP, both with and without VR. The last minute of these 3-min trials was used for analysis. After each trial, subjects were asked to subjectively rate whether (1) the walking resembled walking on the street, (2) they could walk at their own preferred walking speed and (3) the walking was fatiguing, on a scale from 1 (not) to 10 (yes). To obtain one overall score, these ratings were averaged to a total subjective score [16].

Ground reaction forces and moments were recorded by the force sensors underneath each belt (50x200 cm) at 1000 Hz and 3D motion data was captured at 100 Hz (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada). Technical clusters of three markers were attached to the pelvis, thighs, shanks and feet. During a static trial anatomical landmarks were indicated in order to anatomically calibrate the technical cluster frames [18].

Data analysis

Force data were downsampled to 100 Hz and force and motion data were low-pass filtered at 6 Hz (bidirectional 4th-order Butterworth filter). Initial contact and toe-off were based on vertical ground reaction forces (50 N threshold). Strides with foot placement on both belts were excluded from further analysis. 3D kinematics and kinetics were analyzed using custom-made software (www.BodyMech.nl, The Mathworks). Joint and segment angles were calculated following CAMARC anatomical frame definitions [19] and time-normalized to 0-100% of the gait cycle. The right leg was analyzed in TD children and the most affected leg in children with CP. From the marker data and belt speed we calculated walking speed, stride length, stride time, step width and stance percentage as well as the average between-stride walking speed variability. To compare the time-scale of the walking speed variability between conditions, the walking speed was low pass filtered at 6 Hz (bidirectional 2th-order Butterworth filter) and Fourier transformed to the frequency domain. From the kinematic and kinetic curves, conventional clinically relevant features of the gait pattern were calculated, including the kinematic parameters as used in the Gillette Gait Index [20], the peak and range values of moments, the ankle peak power and the work (*i.e.* area under the power curve) for the hip, knee and ankle.

Statistics

Linear generalized estimating equations (GEE) analyses were performed, because this analysis allows for repeated measures, can correct for walking speed differences between subjects and conditions without the need for assumptions of normal distribution or homogeneity of variance, and can deal with missing data. The working correlation structure was set at exchangeable and based on robust estimation (SPSS, v20). The effects were examined at the average walking speed over all conditions and subjects (1.20 m/s).

First, possible main effects of SP, VR and group (CP versus TD) were determined following the model:

$$\text{Outcome} = b_0 + b_1(\text{SP}) + b_2(\text{VR}) + b_3(\text{GR}) + \ldots$$
$$b_6(\text{speed}) + b_7(\text{GR x speed}) + \varepsilon \qquad 9.1$$

with b_0 the regression coefficient representing the intercept value (at average walking speed) of the outcome measure during FS walking without VR for TD; b_1 the average difference in outcome measure at average walking speed between SP and FS walking (effect size of main SP effect); b_2 main VR effect; b_3 main group effect; b_6 the average slope of the outcome measures versus speed, *i.e.* correction for differences from average walking speed; b_7 differences in slope between groups, *i.e.* correction for interaction effects between speed and group; and ε the residual error term. The terms correcting for confounders (b_6 and b_7) were only included if they were significant or if inclusion resulted in more than 10% change in the SP, VR or GR coefficients. When testing the effects on walking speed and the subjective ratings, the confounders were not included. Effects were considered significant if $p<0.05$.

Second, we examined if the effect of SP and VR were dependent on group using a model which included the interactions terms:

$$\text{Outcome} = b_0 + b_1(\text{SP}) + b_2(\text{VR}) + b_3(\text{GR}) + b_4(\text{SP x GR}) + \ldots$$
$$b_5(\text{VR x GR}) + b_6(\text{speed}) + b_7(\text{GR x speed}) + \varepsilon \qquad 9.2$$

with b_1 now as the average difference in outcome measure between SP and FS walking

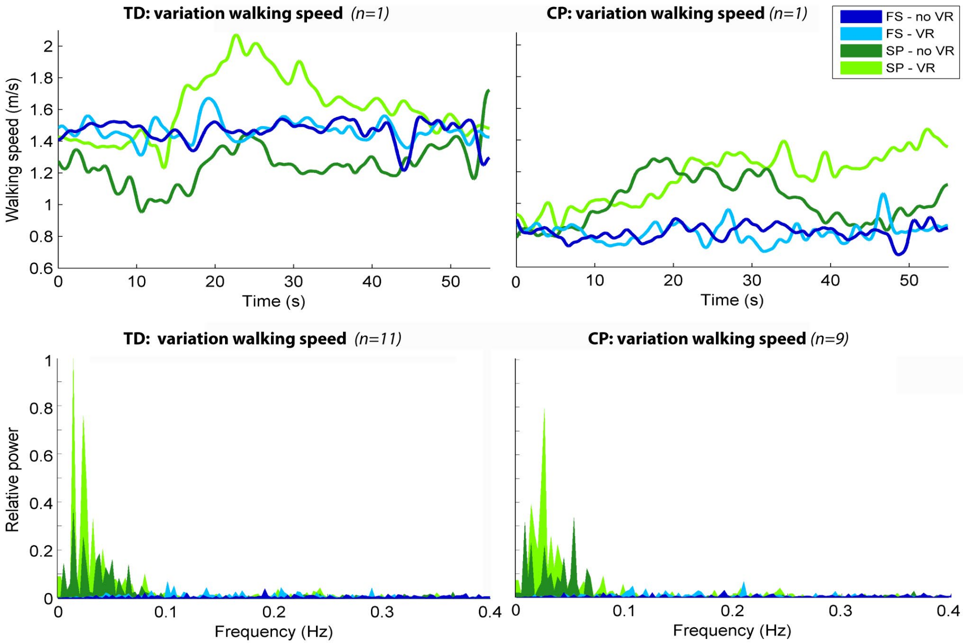

Fig 9-1. Variations in walking speed. Top: examples of walking speed over time for different conditions, for a TD and CP subject. Bottom: the power spectral density of the normalized walking speed of all TD and CP subjects per condition, showing more low-frequency content in SP.

for TD subjects; b_2 the difference between walking with and without VR for TD subjects; b_3 the difference between CP and TD at FS without VR; b_4 the additional effect of SP for CP; and b_5 the additional effect of VR for CP. The speed corrections terms remained the same and were included under the same conditions.

Results

Effect of group

All children were able to walk in all conditions. For two children with CP, the trials without VR could not be collected for technical reasons. Children with CP walked 24.9% slower than TD children (p=0.02), with a trend of increased between-stride walking speed variability (p=0.07). They also showed several expected differences in kinematics and kinetics compared with TD (Table 9-1). There was no difference in subjective rating between CP and TD (Table 9-1).

Effect of SP

Subjects walked 7.3% faster in SP compared to FS (p=0.004). Between-stride variability was 2.1 times increased in SP (p<0.001; Table 9-1), with more speed fluctuation over multiple strides illustrated by the predominance of low frequencies in CP compared with FS (Fig. 9-1). An effect of SP on kinematics and kinetics was only found for the maximum ankle extension moment, with a 1.9% increase in SP (p=0.04). There was no difference in subjective rating between SP and FS walking.

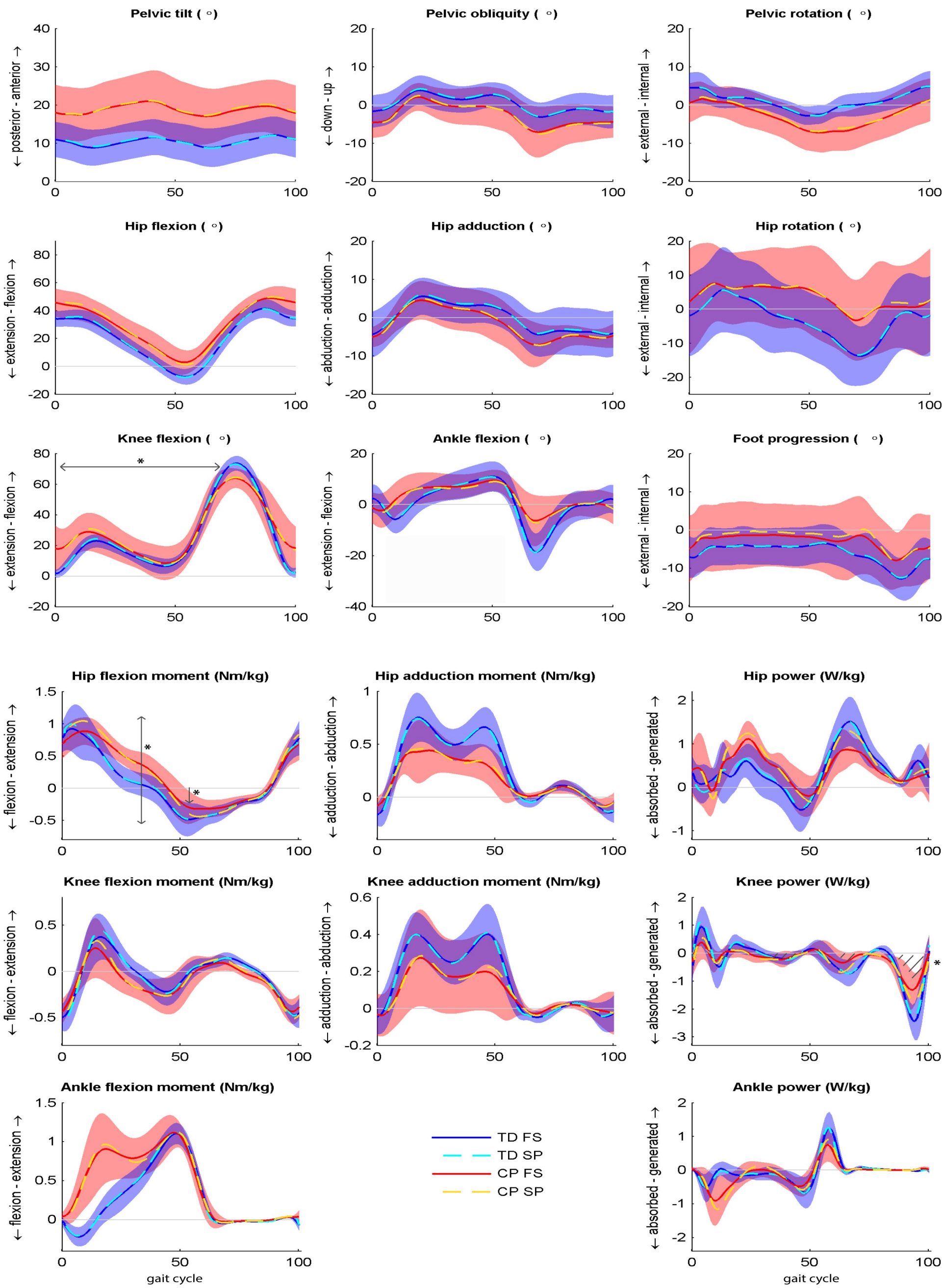

Fig 9-2. Kinematic and kinetic curves comparing FS and SP walking for TD children and children with CP, averaged over VR conditions, with mean and standard deviations. Note that these data were not corrected for differences in walking speed. Stars and arrows indicate significant interaction effects between SP and group for the key parameters as shown in Table 9-1.

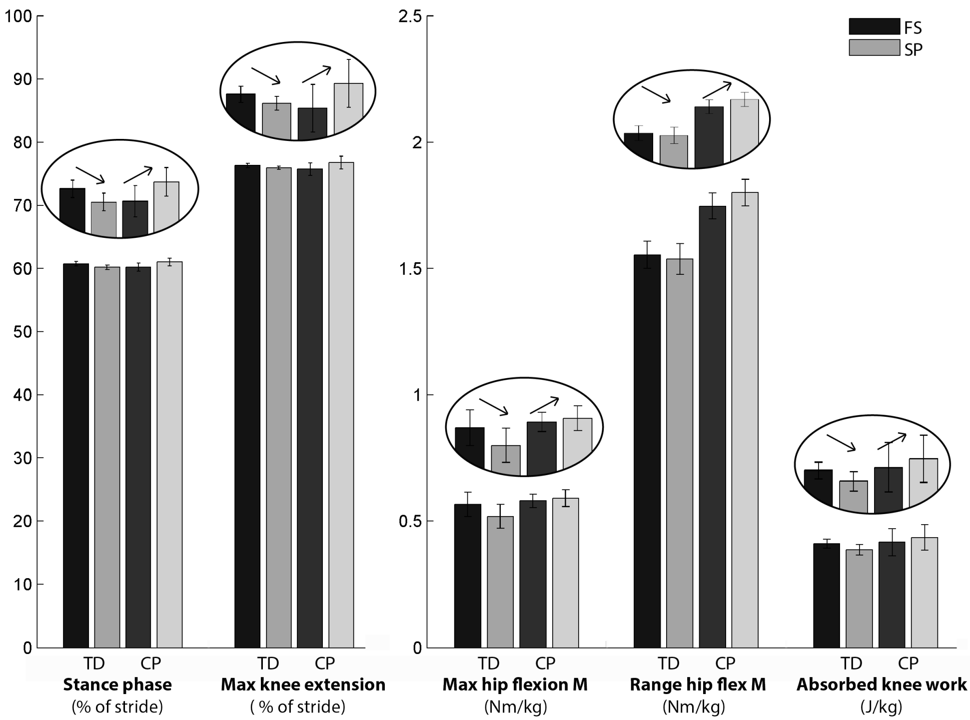

Fig 9-3. Interaction effect between SP and group for the significant parameters (average and standard error), with inset enlargements to highlight the small differences between conditions.

For five out of 33 parameters, significant but small interaction effects were found between SP and group (Table 9-2; Fig. 9-2). For TD, stance percentage was decreased in SP compared with FS walking, while it was increased for CP (p<0.01). A similar interaction effect was found for time to maximum knee flexion (p<0.01), maximum and range of hip flexion moment (p=0.02 and p<0.05) and absorbed knee work (p<0.01; Fig. 9-3). The subjective rating showed a similar trend; TD tended to prefer SP over FS while CP preferred FS (p=0.08).

Effect of VR

There was no effect of VR on walking speed and its variability. An effect of VR on kinematics and kinetics was only found for the absorbed ankle work, with a 5.8% increase in SP (p=0.03). The subjective rating of walking with VR was 3% higher than without VR (p=0.018; Table 9-1). An interaction between VR and group was only found for range of hip extension (Appendix 9-A), which decreased with VR for TD and increased with VR for CP (effect size: 1.0^o; p=0.03), and between-stride walking speed variability, which increased with VR for TD and decreased with VR for CP (effect size: 0.03 m/s; p=0.02).

Table 9-1: main effects of SP, VR and group

Parameters	Effect of SP			Effect of VR			Group effect		
	FS	SP		No VR	VR		TD	CP	
	Mean±Std	Mean±Std	*p*	Mean±Std	Mean±Std	*p*	Mean±Std	Mean±Std	*p*
Subjective rating	8.31± 0.35	8.2 ± 0.33	0.75	8.17 ± 0.35	8.42 ± 0.33	0.02	8.48 ± 0.25	8.10 ± 0.62	0.57
Spatio-temporal									
Speed (m/s)	1.087 ± 0.067	1.166 ± 0.072	<0.01	1.101 ± 0.088	1.151 ± 0.056	0.31	1.287 ± 0.059	0.966 ± 0.126	0.02
Speed var (m/s)	0.040 ± 0.002	0.084 ± 0.008	<0.01	0.064 ± 0.005	0.060 ± 0.005	0.49	0.054 ± 0.005	0.070 ± 0.006	0.07
Stride length (m)	1.242 ± 0.027	1.248 ± 0.025	0.38	1.244 ± 0.026	1.245 ± 0.026	0.85	1.280 ± 0.032	1.210 ± 0.040	0.16
Stride time (s)	1.042 ± 0.023	1.051 ± 0.022	0.21	1.045 ± 0.023	1.047 ± 0.022	0.76	1.072 ± 0.028	1.020 ± 0.034	0.25
Step width (m)	0.139 ± 0.008	0.138 ± 0.008	0.61	0.140 ± 0.007	0.137 ± 0.008	0.35	0.120 ± 0.007	0.157 ± 0.013	0.02
Stance time (%)	60.660 ± 0.412	60.619 ± 0.388	0.87	60.566 ± 0.378	60.713 ± 0.406	0.42	60.487 ± 0.346	60.791 ± 0.629	0.65
Kinematics									
Trunk fw lean (°)	8.413 ± 1.358	7.988 ± 1.276	0.37	8.614 ± 1.351	7.786 ± 1.296	0.12	7.579 ± 1.669	8.822 ± 2.078	0.65
Pelvic tilt mean (°)	14.923 ± 1.408	15.021 ± 1.484	0.65	15.110 ± 1.456	14.834 ± 1.436	0.15	10.024 ± 1.387	19.920 ± 2.562	<0.01
Pelvic tilt range (°)	6.220 ± 0.301	6.146 ± 0.322	0.37	6.255 ± 0.307	6.112 ± 0.321	0.19	5.309 ± 0.300	7.058 ± 0.544	<0.01
Pelvic int rot mean (°)	-0.832 ± 0.766	-0.819 ± 0.780	0.96	-0.639 ± 0.765	-1.012 ± 0.772	0.08	1.019 ± 0.632	-2.669 ± 1.407	0.02
Hip ext max (°)	3.299 ± 1.478	3.312 ± 1.457	0.94	3.341 ± 1.443	3.271 ± 1.496	0.76	7.305 ± 1.662	-0.693 ± 2.403	<0.01
Hip ext range (°)	50.946 ± 0.930	50.924 ± 1.038	0.94	51.153 ± 0.956	50.716 ± 1.008	0.09	48.747 ± 0.965	53.122 ± 1.701	0.03
Hip abd sw max (°)	7.784 ± 1.061	7.484 ± 1.093	0.11	7.737 ± 1.084	7.531 ± 1.066	0.12	5.897 ± 1.805	9.371 ± 1.251	0.11
Hip int rot st mean (°)	-2.143 ± 2.481	-2.156 ± 2.558	0.93	-2.143 ± 2.481	-2.156 ± 2.558	0.94	0.821 ± 3.262	-5.121 ± 3.845	0.24
Knee flex at IC (°)	9.715 ± 2.489	9.564 ± 2.380	0.68	10.015 ± 2.546	9.264 ± 2.326	0.09	0.898 ± 0.967	18.381 ± 4.776	<0.01
Knee flex timing (%)	76.274 ± 0.599	76.413 ± 0.583	0.57	76.318 ± 0.613	76.369 ± 0.573	0.85	76.163 ± 0.297	76.524 ± 1.073	0.74
Knee flex range (°)	68.745 ± 2.257	68.495 ± 2.423	0.64	68.478 ± 2.382	68.762 ± 2.310	0.60	75.523 ± 1.519	61.717 ± 4.448	<0.01
Ankle flex st max (°)	10.917 ± 1.142	10.818 ± 1.240	0.57	10.777 ± 1.205	10.957 ± 1.183	0.43	11.724 ± 1.752	10.011 ± 1.583	0.46
Ankle ext sw max (°)	18.781 ± 1.137	19.152 ± 1.213	0.29	19.106 ± 1.142	18.827 ± 1.203	0.37	22.126 ± 1.742	15.807 ± 1.583	<0.01
Foot int rot mean (°)	-2.803 ± 1.543	-2.830 ± 1.440	0.94	-2.634 ± 1.503	-2.998 ± 1.472	0.17	-4.798 ± 1.429	-0.834 ± 2.600	0.18

Table 9-1: continuation

Parameters	Effect of SP			Effect of VR			Group effect		
	FS	SP		No VR	VR		TD	CP	
	Mean ± Std	Mean ± Std	*p*	Mean ± Std	Mean ±Std	*p*	Mean ± Std	Mean ± Std	*p*
Kinetics									
Hip flex M max (Nm/kg)	0.586 ± 0.030	0.558 ± 0.030	0.08	0.564 ± 0.029	0.579 ± 0.030	0.37	0.544 ± 0.045	0.600 ± 0.035	0.32
Hip flex M range (Nm/kg)	1.663 ± 0.039	1.671 ± 0.041	0.69	1.669 ± 0.037	1.666 ± 0.042	0.85	1.548 ± 0.055	1.787 ± 0.054	<0.01
Hip abd M max (Nm/kg)	0.704 ± 0.045	0.709 ± 0.050	0.66	0.710 ± 0.049	0.703 ± 0.046	0.45	0.835 ± 0.066	0.577 ± 0.069	<0.01
Hip gen W (J/kg)	0.575 ± 0.035	0.562 ± 0.036	0.21	0.573 ± 0.037	0.564 ± 0.034	0.33	0.464 ± 0.039	0.672 ± 0.062	<0.01
Hip abs W (J/kg)	0.123 ± 0.013	0.114 ± 0.013	0.16	0.119 ± 0.013	0.118 ± 0.013	0.87	0.116 ± 0.019	0.121 ± 0.018	0.86
Knee ext M max (Nm/kg)	0.416 ± 0.053	0.450 ± 0.050	0.12	0.429 ± 0.053	0.437 ± 0.048	0.53	0.443 ± 0.057	0.422 ± 0.082	0.83
Knee abd M max (Nm/kg)	0.430 ± 0.045	0.429 ± 0.047	0.89	0.427 ± 0.046	0.432 ± 0.045	0.45	0.483 ± 0.038	0.376 ± 0.087	0.28
Knee gen W (J/kg)	0.154 ± 0.012	0.159 ± 0.013	0.46	0.157 ± 0.014	0.155 ± 0.012	0.79	0.179 ± 0.018	0.133 ± 0.015	0.05
Knee abs W (J/kg)	0.422 ± 0.027	0.413 ± 0.027	0.31	0.415 ± 0.027	0.420 ± 0.027	0.51	0.399 ± 0.019	0.436 ± 0.054	0.54
Ankle ext M max (Nm/kg)	1.219 ± 0.048	1.242 ± 0.050	0.04	1.222 ± 0.047	1.239 ± 0.050	0.12	1.168 ± 0.044	1.293 ± 0.088	0.21
Ankle P max (W/kg)	1.282 ± 0.107	1.298 ± 0.098	0.75	1.256 ± 0.106	1.323 ± 0.099	0.11	1.472 ± 0.124	1.108 ± 0.160	0.08
Ankle gen W (J/kg)	0.127 ± 0.011	0.124 ± 0.011	0.52	0.126 ± 0.012	0.125 ± 0.010	0.84	0.132 ± 0.013	0.118 ± 0.019	0.55
Ankle abs W (J/kg)	0.194 ± 0.015	0.198 ± 0.016	0.33	0.191 ± 0.016	0.202 ± 0.016	0.03	0.172 ± 0.015	0.220 ± 0.027	0.12

With var. variance; Fw. forward; int. internal; max. maximum; ext. extension; flex. flexion; abd. abduction; sw. swing; st. stance; rot. rotation; IC initial contact; progr. progression; M moment; P power; and W work. Given values are estimated means and standard deviations at average walking speed resulting from the model.

Discussion

This study aimed to examine the effect of treadmill speed mode and VR on treadmill walking in TD children and children with CP. Differences were primarily found between TD and CP reflecting the pathological gait pattern generally seen in CP patients. We found that during SP walking the walking speed and its between-stride variability was increased. There was no consistent effect of VR on the kinematics and kinetics, but subjects perceived walking with VR as slightly more similar to overground walking. A few small interactions effects were found between SP and group, but not between VR and group.

The increased walking speed (7.3%) found during SP walking is suggested to be related to long term habituation to this type of treadmill walking, since preferred fixed speed was determined by a baseline SP trial while the experimental SP trial was randomized. Such habituation also occurred in able-bodied adults and transtibial amputee patients [6,15,21]. Although SP walking speed increased with time, a (different) effect of fatigue in CP and TD cannot be ruled out. However, the four conditions were randomized and the trials were relatively short with time to rest in between, thus it is assumed that fatigue did not play a major role in both groups. The increased between-stride walking speed variability in SP was present in both TD and CP. The increase in variability was higher than found in able-bodied adults (110% versus 54% increase), but consisted of a similar increase in fluctuations over multiple strides [3]. Because the increased variability was not related to fast changes between consecutive strides, it is unlikely that they reflect balance compensations, but rather the spontaneous long-term variations seen during normal overground walking [4,5].

When compensating for walking speed differences, SP was not found to affect the kinematics and kinetics. The only effect of SP was on the maximum ankle extension moment, which was very small (1.9%) and not consistent with previous results for able-bodied adults [3]. A small interaction effect between SP and group was found for five out of 33 parameters. The general pattern was that, when controlling for speed differences, children with CP had a slightly more cautious gait pattern, mainly illustrated by an increased stance percentage during SP compared to FS walking. TD children showed the opposite pattern, which is in line with the slightly improved gait found during SP walking in able-bodied adults [3]. In addition, there was a trend of TD children rating SP as more similar to overground walking while it was perceived as less similar by children with CP. This suggests that some children with CP might need more time to adjust to SP walking than the TD children, although the effects on the gait pattern are minimal.

Although there was no consistent main or interaction effect of VR on the gait pattern, both TD and CP perceived walking with VR as more similar to normal overground walking. This is in line with the findings for the able-bodied adults [15]. Previously, the effect of VR was also found to be dependent on treadmill speed mode in able-bodied adults, with a slightly more cautious gait with VR at SP [15]. Therefore, we did an additional analysis to determine whether the lack of main VR effects in both groups was due to the pooling of SP and FS walking. An interaction effect of VR and SP was only found for 2 parameters with small differences (*i.e.* mean pelvic tilt and

peak knee extension moment decreased with VR at FS and increased with VR at SP; effect size: 0.7°, p=0.02 and 0.06 Nm/kg, p=0.04 respectively). Thus, even when taking the groups or walking speed mode into account, VR did not consistently affect the gait of the children and could thus be used for clinical gait analysis or training. However, for a thorough understanding of the influence of VR on gait, more research is warranted on the effect of different sceneries, including more challenging surroundings as walking in a city with other pedestrians, varying speeds of optical flow and the actual focus of attention of subjects using techniques such as eye tracking.
It should be noted that we measured only a small sample of children, with relatively large between-subject variability in the CP group [22] and with missing trials for two subjects. This lowers the power of the study, so smaller (interaction) effects of SP and group might not have been found. Despite this, the changes that we did find were very small, even smaller than the average within-stride variation for TD (for FS without VR), which is consistent with the small effect sizes found in previous studies in able-bodied adults [3,6]. In addition, the multiple statistical testing could have resulted in a coincidentally significant differences. Therefore, the few and small differences that were found could be considered not to be clinically relevant.

These findings suggest that SP and FS walking, with and without VR, can be used interchangeably for treadmill-based clinical gait analysis. This opens the door for clinical treadmill-based fatigue and stride variability analysis using SP walking by allowing subjects to (slowly) adjust their walking speed. In addition, the use of a VR environment can create a motivational environment that is perceived as more similar to overground walking and has the ability to provide feedback to train subjects or to challenge them out of their comfort zone. Even though no relevant effects were found for SP and VR walking at group level, it should be taken into account that for some children, larger differences were found between conditions. This could be related to a difference in the ease at which patients with CP learn to walk at the SP mode and handle the extra input provided by VR. In addition, the results cannot be automatically translated to the entire spectrum of ambulant patients with CP, because we only measured relatively good walkers. Further investigation is needed to examine the effects of SP and VR in a larger group of patients with CP, including those with more severe gait limitations, and to relate these changes to conventional overground gait analysis.

Conclusion

Treadmill speed mode and VR did not cause clinically relevant changes in the kinematic or kinetic parameters of TD children or children with CP. Small interaction effects were found between SP and group, suggesting that children with CP need more time to adjust to SP walking than TD children. These differences were, however, too small to be relevant for clinical gait analysis. The results indicate that both SP and FS walking, with and without VR, can be used interchangeably for treadmill-based clinical gait analysis. Potential advantages of SP and VR were found, consisting of the increased walking speed variability during SP walking and the creation of an environment that better resembled normal overground walking with a VR.

Table 9-2. Interaction effect between SP and group

	TD		CP			
	FS	SP	FS	SP		
Parameters	mean ± std	mean ± std	mean ± std	mean ± std	*p*	effect
Subjective rating	8.42±0.25	8.55±0.28	8.22 ±0.66	7.94±0.59	0.08	-0.41
Spatio-temporal						
Speed (m/s)	1.266±0.066	1.307±0.057	0.903 ±0.120	1.028±0.134	0.10	0.083
Speed var (m/s)	0.037±0.003	0.072±0.009	0.042 ±0.003	0.100±0.012	0.14	0.023
Stride length (m)	1.274±0.033	1.284±0.031	1.211 ±0.043	1.209±0.038	0.33	-0.012
Stride time (s)	1.070±0.029	1.075±0.028	1.012 ±0.039	1.025±0.035	0.68	0.007
Step width (m)	0.121±0.008	0.119±0.007	0.150 ±0.014	0.154±0.014	0.38	0.006
Stance time (%)	60.725±0.367	60.177±0.364	60.213 ±0.658	61.012±0.603	<0.01	1.346
Kinematics						
Trunk fw lean (°)	7.765±1.798	7.373±1.584	9.020 ±2.216	8.645±2.148	0.99	-0.270
Pelvic tilt mean (°)	10.052±1.340	9.962±1.425	19.512 ±2.402	19.982±2.593	0.26	0.560
Pelvic tilt range (°)	5.395±0.284	5.265±0.328	7.078 ±0.615	7.076±0.576	0.57	0.128
Pelvic int rot mean (°)	1.000±0.632	1.047±0.679	-2.593 ±1.389	-2.684±1.432	0.79	-0.137
Hip ext max (°)	7.318±1.659	7.296±1.678	-0.718 ±2.498	-0.665±2.374	0.82	-0.074
Hip ext range (°)	48.911±0.943	48.523±0.991	52.524 ±1.544	53.168±1.770	0.16	1.031
Hip abd sw max (°)	6.024±1.772	5.770±1.836	9.636 ±1.230	9.232±1.230	0.68	0.149
Hip int rot st mean (°)	-0.875±3.271	-0.720±3.255	5.481 ±3.677	5.155±3.853	0.19	-0.482
Knee flex at IC (°)	0.985±1.010	0.833±0.960	18.386 ±5.041	18.277±4.697	0.96	0.043
Knee flex timing (%)	76.310±0.353	75.930±0.289	75.717 ±1.014	76.763±1.008	<0.01	1.426
Knee flex range (°)	75.684±1.357	75.331±1.660	61.579 ±4.280	61.580±4.555	0.77	0.353
Ankle flex st max (°)	11.763±1.698	11.627±1.801	9.955 ±1.347	9.960±1.639	0.76	0.141
Ankle ext sw max (°)	21.959±1.693	22.308±1.805	15.653 ±1.547	16.006±1.632	0.99	-0.004
Foot int rot mean (°)	-4.732±1.585	-4.883±1.340	-1.079 ±2.649	-0.826±2.619	0.50	0.403
Kinetics						
Hip flex M max (Nm/kg)	0.566±0.048	0.518±0.047	0.581 ±0.026	0.591±0.034	0.02	0.059
Hip flex M range (Nm/kg)	1.554±0.054	1.537±0.060	1.747 ±0.051	1.800±0.052	<0.05	0.070
Hip abd M max (Nm/kg)	0.833±0.061	0.836±0.070	0.574 ±0.069	0.580±0.071	0.90	-0.003
Hip gen W (J/kg)	0.479±0.038	0.453±0.041	0.663 ±0.061	0.672±0.062	0.07	0.035
Hip abs W (J/kg)	0.122±0.020	0.111±0.020	0.124 ±0.020	0.117±0.018	0.79	-0.003
Knee ext M max (Nm/kg)	0.428±0.062	0.458±0.056	0.397 ±0.082	0.441±0.083	0.72	0.014
Knee abd M max (Nm/kg)	0.483±0.035	0.483±0.040	0.379 ±0.088	0.375±0.088	0.85	-0.004
Knee gen W (J/kg)	0.173±0.017	0.179±0.018	0.126 ±0.015	0.131±0.014	0.95	-0.001
Knee abs W (J/kg)	0.410±0.018	0.387±0.021	0.417 ±0.053	0.435±0.051	<0.01	-0.042
Ankle ext M max (Nm/kg)	1.156±0.043	1.180±0.046	1.283 ±0.089	1.304±0.088	0.91	-0.003
Ankle P max (W/kg)	1.461±1.323	1.482±0.125	1.108 ±0.176	1.115±0.155	0.88	-0.013
Ankle gen W (J/kg)	0.135±0.012	0.129±0.012	0.112 ±0.019	0.117±0.018	0.09	0.011
Ankle abs W (J/kg)	0.171±0.016	0.173±0.016	0.216 ±0.026	0.223±0.028	0.64	-0.004

With var. variance; fw. forward; int. internal; max. maximum; ext. extension; flex. flexion; abd. abduction; sw. swing; st. stance; int. internal; rot. rotation; IC initial contact; progr. progression; M moment; P power; gen. generated; abs. absorbed; and W work. Given values are estimated means and standard deviations at average walking speed resulting from the model.

Table 9-A. Interaction effect between VR and group

	TD		CP			
	FS	SP	FS	SP		
Parameters	mean ± std	mean ± std	mean ± std	mean ± std	*p*	effect
Subjective rating	8.43 ±0.26	8.54±0.25	7.84±0.66	8.32±0.60	0.09	0.373
Spatio-temporal						
Speed (m/s)	1.291±0.060	1.283±0.061	0.905±0.169	1.026±0.090	0.21	0.129
Speed var (m/s)	0.051±0.003	0.058±0.003	0.082±0.010	0.060±0.005	0.02	-0.029
Stride length (m)	1.283±0.033	1.275±0.030	1.202±0.040	1.218±0.041	0.07	0.024
Stride time (s)	1.075±0.031	1.070±0.026	1.013±0.035	1.025±0.037	0.17	0.017
Step width (m)	0.120±0.007	0.119±0.008	0.155±0.014	0.150±0.014	0.42	-0.004
Stance time (%)	60.398±0.338	60.503±0.396	60.546±0.611	60.680±0.652	0.94	0.029
Kinematics						
Trunk fw lean (°)	-7.601±1.660	-7.536±1.713	-9.853±2.337	-7.812±2.040	0.08	1.975
Pelvic tilt mean (°)	10.231±1.340	9.783±1.373	19.760±2.503	19.734±2.481	0.21	0.422
Pelvic tilt range (°)	5.409±0.275	5.252±0.345	7.138±0.607	7.016±0.576	0.87	0.035
Pelvic int rot mean (°)	1.325±0.641	0.722±0.640	-2.638±1.412	-2.639±1.411	0.17	0.603
Hip ext max (°)	-7.377±1.647	-7.237±1.698	0.709±2.383	0.674±2.492	0.68	-0.175
Hip ext range (°)	49.143±0.987	48.291±0.957	52.762±1.515	52.930±1.742	0.03	1.021
Hip abd sw max (°)	-5.964±1.827	-5.830±1.777	-9.591±1.198	-9.277±1.259	0.53	0.179
Hip int rot st mean (°)	-0.801±3.240	-0.793±3.286	5.296±3.656	5.340±3.873	0.92	0.036
Knee flex at IC (°)	1.304±1.149	0.513±0.861	18.675±5.092	17.988±4.621	0.91	0.104
Knee flex timing (%)	76.219±0.338	76.022±0.332	76.056±1.070	76.424±0.994	0.35	0.565
Knee flex range (°)	75.349±1.790	75.666±1.231	61.471±4.356	61.688±4.442	0.92	-0.101
Ankle flex st max (°)	11.518±1.750	11.872±1.751	10.012±1.553	9.903±1.452	0.36	-0.462
Ankle ext sw max (°)	-22.400±1.722	-21.867±1.777	-15.768±1.484	-15.890±1.642	0.32	-0.655
Foot int rot mean (°)	-4.668±1.335	-4.947±1.584	-0.694±2.787	-1.211±2.458	0.65	-0.238
Kinetics						
Hip flex M max (Nm/kg)	0.534±0.047	0.550±0.050	0.581±0.031	0.591±0.028	0.81	-0.007
Hip flex M range (Nm/kg)	1.547±0.052	1.544±0.062	1.777±0.049	1.769±0.052	0.86	-0.005
Hip abd M max (Nm/kg)	-0.837±0.066	-0.832±0.065	-0.582±0.073	-0.572±0.066	0.74	0.006
Hip gen W (J/kg)	0.473±0.039	0.459±0.039	0.668±0.065	0.667±0.057	0.51	0.013
Hip abs W (J/kg)	-0.119±0.020	-0.114±0.020	-0.118±0.020	-0.124±0.018	0.28	0.012
Knee ext M max (Nm/kg)	0.434±0.063	0.452±0.052	0.423±0.083	0.415±0.081	0.28	-0.025
Knee abd M max (Nm/kg)	0.483±0.036	0.483±0.040	0.371±0.090	0.384±0.085	0.39	0.012
Knee gen W (J/kg)	0.178±0.019	0.174±0.017	0.129±0.016	0.128±0.013	0.83	0.003
Knee abs W (J/kg)	-0.398±0.019	-0.399±0.021	-0.421±0.052	-0.431±0.052	0.60	-0.008
Ankle ext M max (Nm/kg)	1.161±0.042	1.175±0.047	1.283±0.086	1.304±0.091	0.77	0.007
Ankle P max (W/kg)	1.432±0.133	1.511±0.124	1.087±0.167	1.136±0.162	0.69	-0.030
Ankle gen W (J/kg)	0.133±0.014	0.131±0.011	0.115±0.020	0.115±0.018	0.74	0.003
Ankle abs W (J/kg)	-0.167±0.015	-0.177±0.016	-0.213±0.027	-0.226±0.028	0.74	-0.004

With var. variance; fw. forward; int. internal; max. maximum; ext. extension; flex. flexion; abd. abduction; sw. swing; st. stance; int. internal; rot. rotation; IC initial contact; progr. progression; M moment; P power; gen. generated; abs. absorbed; and W work. Given values are estimated means and standard deviations at average walking speed resulting from the model.

Acknowledgements

The authors thank Tessa Hoekstra and Lianne Kraan for assistance in data collection. This study was financially supported by grant 10733 from the Dutch Technology Foundation STW and by Motek Medical.

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