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

10 Treadmill versus overground: kinematic comparison in CP

Treadmill walking offers several advantages for clinical gait analysis and gait training, but may affect gait parameters. We compared walking on a self-paced treadmill in a virtual environment (TM^+) with overground walking in a conventional gait lab (OG), and with natural walking (NW) outside a lab environment on a GaitRite measurement mat, for 11 typically developing (TD) children and 9 children with cerebral palsy (CP). Spatiotemporal parameters and subjective scores on similarity to normal walking were compared between all three conditions, while kinematic parameters and Gait and Motion Analysis Profile Scores (GPS and MAP) were compared between OG and TM^+. Subjects walked slower and with shorter strides in both lab conditions compared to NW. Stride width was 3 to 4 cm wider in TM^+ than in OG and NW. Mean kinematic curves showed a few differences between OG and TM^+: on the treadmill children with CP walked with on average 2° more pelvic tilt, 7° more knee flexion at initial contact, and more deviating knee and ankle kinematics as indicated by the MAP scores. These differences may in part be due to increased fatigue in TM^+ as a result of longer continuous walking time. Our results indicate that differences between self-paced treadmill walking in a VR and walking in a conventional gait lab are generally small, but need to be taken into account when performing gait analysis on a treadmill.

MM van der Krogt, LH Sloot & J Harlaar (2014). Overground versus self-paced treadmill walking in a virtual environment in children with cerebral palsy. Gait & Posture, 40(4), 587-593

Introduction

Instrumented treadmills are increasingly used in clinical gait analysis and gait (re) training, since they have several advantages over conventional overground gait labs. Treadmill walking allows for continuous gait and the measurement of many consecutive steps within a small measurement area. Recent developments have led to high quality instrumented treadmills, which can be placed in a virtual reality environment to allow for a natural, moving visual scene (optical flow). Real-time analysis software enables direct feedback and interaction with the subject, for instance to continuously adjust the belt speed to the subject's instantaneous walking speed, so called self-paced walking, allowing for natural variations in walking speed [1,2]. These features may enable gait analysis on a treadmill in children with cerebral palsy (CP), allowing them to walk at their own speed and in a realistic environment.

Previous studies have shown however, that differences exist between overground and treadmill walking. On a treadmill, subjects tend to walk slower [3] and with shorter steps and higher (relative) cadence than overground [3-5]. Differences in kinematics, kinetics, and EMG have also been found [6-10], although these were generally smaller than measurement errors [7]. Patient populations such as those with stroke or prostheses generally demonstrate comparable effects of treadmill walking compared to healthy adults [11-13], although in stroke treadmill walking was also found to be more symmetrical than overground walking [12]. The differences between treadmill and overground walking may be due to the fixed, imposed treadmill speed [1], lack of optical flow [14], differences in belt surface [15], or small intra-stride variations in belt speed [7,16]. These differences possibly limit the transfer of gait analysis and training outcomes on a treadmill to overground walking.

The combination of a realistic virtual environment providing an optical flow and self-paced walking may make treadmill walking more similar to overground, but this has never been investigated. Furthermore, most studies comparing normal treadmill and overground walking evaluated adult populations, and it is not known whether the effects are any different in children with and without pathology, nor whether (potential) differences are clinically relevant. Different effects of treadmill walking for children are likely, especially for those with CP, since they have more stride-to-stride variability in their walking speed and gait pattern [17], a lower dynamic stability [18], and as a result they may have more difficulty adjusting to the altered environment.

The aim of this study was to compare self-paced treadmill walking in a realistic virtual environment to walking in a conventional overground gait lab, and to natural walking outside of a lab environment, both in children with CP and typically developing (TD) children. The study was set up in order to see whether treadmill walking could replace overground walking for clinical gait analysis.

Methods

Twenty children participated in this cross-sectional study: 11 TD children (4 female; age 10.6±2.2 years, range 8-15; height 1.52±0.15 m; weight 38.2±10.5 kg) and 9 children with spastic CP (5 female; age 11.6±2.1 years, range 8-14; height 1.49±0.13 m; weight 40.9±10.3 kg). There were no statistical differences between groups in terms of age, height, or weight. The inclusion criteria were that children with CP had to be able to walk independently without walking aids for at least 5 min on end and 30 min total within two h, were classified as level I or II on the gross motor function classification scale (GMFCS) [19]; had received no multilevel surgery, selective dorsal rhizotomy or baclofen treatment within the last year; nor botulinum toxin A treatment within the previous 16 weeks. CP patients fulfilling these criteria were randomly selected from the department's database, and all subjects who agreed to take part were able to fulfill the entire protocol and could be included. Two CP patients were unilaterally affected and 7 bilaterally, 4 of whom with one clearly more affected side. Two subjects had received SDR in the past and one a triceps myotenotomy. All parents and children aged 12 years and older provided written informed consent prior to participation. The protocol was approved by the local ethics committee of the VU University Medical Center in Amsterdam.

Study design and materials

All subjects walked in three conditions: overground in a conventional gait lab (OG); on a self-paced treadmill placed in a realistic virtual environment (TM^+); and in an indoor courtyard to allow for natural walking (NW). The order of conditions was randomized, with NW always first or last for practical reasons. For comfort reasons, subjects wore their own low, flat-soled shoes, including insoles (1 subject) or orthoses (3 subjects) if used daily. In all conditions, subjects were instructed to walk at their own preferred, comfortable walking speed.

OG (Fig. 10-1A) consisted of a 10m walkway with two embedded force plates. At least 5 successful trials were collected for both the left and the right leg, as defined by a full hit of one of the force plates.

TM^+ (Fig. 10-1B) consisted of a dual-belt instrumented treadmill (R-Mill, Forcelink, the Netherlands) in a speed-matched virtual environment projected on a 180° semi-cylindrical screen, displaying an endless, straight forest road and scenery (Gait Real-time Analysis Interactive Lab (GRAIL) system, Motek Medical BV, Amsterdam, The

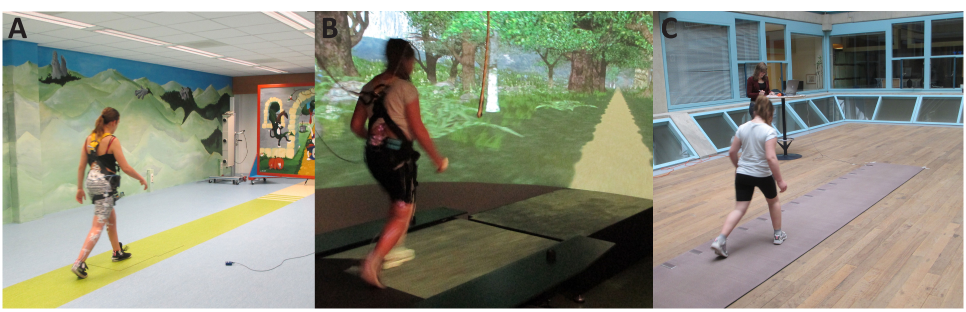

Fig 10-1. Pictures of the three different conditions: (A) conventional gait lab (OG); (B) self-paced treadmill walking in a virtual environment (TM^+); (C) natural walking (NW) in an indoor courtyard over a GaitRite measurement mat.

Netherlands). The speed of the belt was real-time adjusted to match the subject's time-varying walking speed, by means of a self-paced (SP) speed algorithm[1]. Subjects were instructed to walk in the mediolateral middle of the treadmill, but not explicitly to place one foot on each separate belt. Subjects had between 6 and 10 min of habituation time to adjust to the treadmill, the virtual environment, and the SP speed algorithm. Subsequently, as part of a larger protocol, four different 3-min trials were collected in random order (*i.e.* with and without SP mode and with and without a virtual environment), of which the last minute of the trial with virtual environment and in SP mode was evaluated. Subjects wore a safety harness over legs and shoulders loosely hanging from the ceiling, to prevent injury in case of an accidental fall.

In the NW condition (Fig. 10-1C), subjects walked outside of a lab environment in an indoor courtyard. They walked five loops over a 30 m oval track indicated by pylons, without having to stop and start and without any sharp curves. As part of this track, subjects crossed a GaitRite measurement mat five times (CIR Systems, Inc, Sparta, NJ, USA), a 5m long mat with embedded pressure sensors, measuring spatio-temporal parameters. Subjects had no markers or harness attached, to best resemble natural walking.

3D kinematic data were collected for both the OG and TM$^+$ conditions using identical motion capture systems (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada). Technical clusters of three markers were attached to the pelvis, thighs, shanks and feet. Anatomical landmarks were indicated in order to anatomically calibrate the technical cluster frames [20]. The markers remained attached for the entire session and the same indication of anatomical landmarks was used in both labs.

Data analysis and outcome measures

3D kinematic data were analyzed with custom-made software (BodyMech, MatLab, The Mathworks). Joint and segment angles were calculated following CAMARC anatomical frame definitions [21]. Initial contact and toe-off values were calculated following Zeni *et al* [22]. Five right and five left strides were averaged for TD, while for CP five strides of the most affected leg were analyzed. For TM$^+$, five strides in a row were used, randomly selected from the recorded minute.

As outcome measures, 16 clinically important spatiotemporal and kinematic parameters [23] were calculated, along with stride length and stride width (Table 10-2). Stride width was calculated as the mediolateral distance between the left and right heel. For the GaitRite, the heel was defined as the midpoint of the heel imprint. For OG and TM$^+$, the midpoint of the heel was defined as 1/6 of the line connecting the calcaneus marker and the midpoint between MTP I and V markers. Furthermore, as an overall measure of differences in kinematics between labs, the root mean square error (RMSE) between the labs was calculated for all individual joint and segment angles for each subject and averaged over TD and CP separately. As a measure of total gait deviation, the Gait Profile Score (GPS) and the Movement Analysis Profile (MAP) were calculated [24]. The mean OG TD data were used as reference data for the MAP and GPS.

To get a feel for how subjects experienced the different conditions, we collected a subjective score as secondary outcome measure. After each condition, subjects were asked orally to score on a scale of 1 to 10 (similar to a VAS score): (1) the resemblance to walking on the street, (2) whether they could walk at their own preferred speed, and (3) the fatiguing of walking. Since the answers to each of these questions followed the same trend, we took the average of the three answers as overall subjective score. Furthermore, after the entire protocol subjects were asked which lab (OG or TM^+) they preferred in general.

Statistics

All outcome parameters were compared between conditions and between groups using an ANOVA for repeated measurements (IBM SPSS Statistics 20, Armonk, NY, USA). Subjective scores and spatiotemporal parameters, *i.e.* walking speed, cadence, stride length, and stride width, as well as stance percentage and foot progression were compared between OG, TM^+, and NW. In case of a significant difference between conditions, a post hoc test was performed with Bonferroni adjustment. All other kinematic parameters were compared between OG and TM^+ only. If the sphericity assumption was not met, a Huynh-Feldt correction was applied, with p-values of less than 0.05 were considered statistically significant.

Results

After habituation, all children were able to walk independently on the treadmill in self-paced walking mode. One child with CP fell in the safety harness after a sudden stop in self-paced mode, but without any harm.

There were significant differences in spatiotemporal parameters speed, stride length, and stride width between the three conditions (Table 10-1). Children walked fastest during NW, followed by OG and TM^+, with no significant difference between the two labs (p=0.569). TD children walked 6% slower in OG and 8% slower in TM^+ compared to NW. For CP children this was 5% and 14% respectively. The slower speed in both labs was caused especially by a reduction in stride length compared to NW, while cadence was similar in all three conditions. Although not significant, stride length tended to be shorter in TM^+ compared to OG (p=0.060). Stride width was wider in TM^+ compared to both OG and NW, with a difference of 3.0 cm for TD and 3.9 cm for CP on average. All spatiotemporal effects were similar for TD and CP, as indicated by the lack of significant interaction effects.

The average kinematic curves were very similar between OG and TM^+, for both TD and CP, although some significant differences were found (Fig. 10-2, Table 10-1). For both groups, the peak ankle dorsiflexion in swing was approximately 2° less in TM^+ compared to OG. In CP, the knee flexion at initial contact was 6.8° more flexed in TM^+ compared to OG. This effect was not present in TD (interaction p=0.002). The mean pelvic tilt was approximately 2° more anterior in CP in TM^+ compared to OG. This effect was only barely present in TD (0.1° difference; interaction p=0.062).

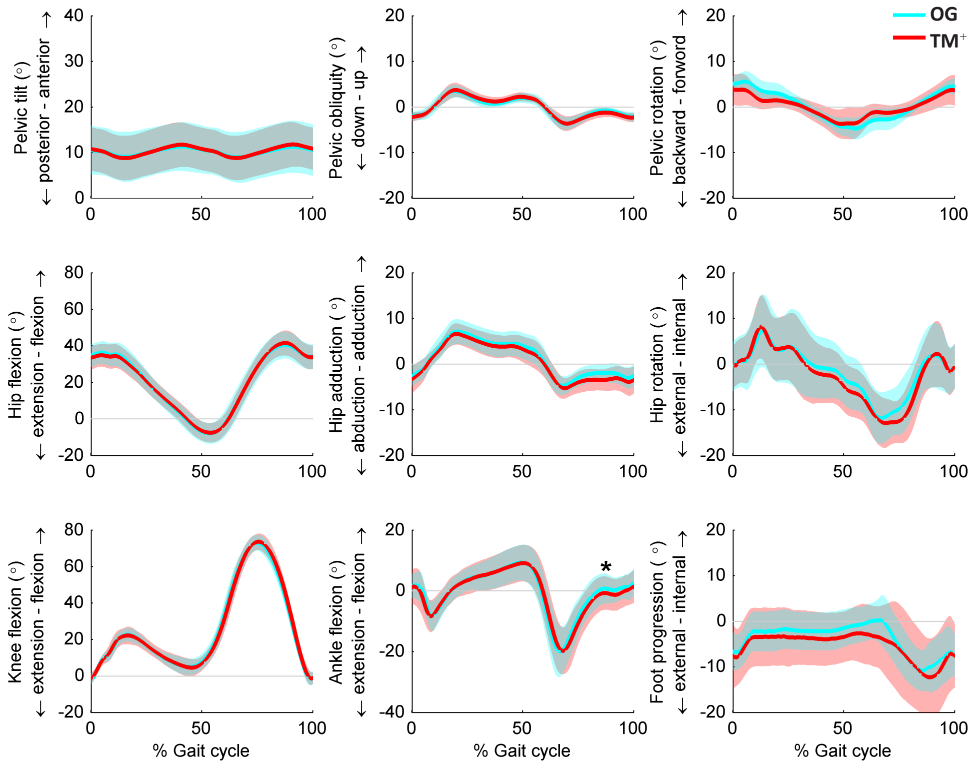

Fig 10-2A. Kinematic curves averaged over TD for conventional gait lab (OG, cyan) and self-paced treadmill walking in a virtual environment (TM^+, red), with standard deviation. Stars and arrows indicate a significant difference in key kinematic parameters (see Table 10-1).

The average difference in kinematics between labs as quantified by the RMSE was higher for CP than for TD, with 3.4° versus 2.4° (Table 10-2; p=0.034 between groups). The variation between subjects was quite large, especially within the CP group. The RMSE ranged from as low as 0.33° (pelvic obliquity of TD subject 8) to as high as 13.8° (knee flexion of CP subject 6; Table 10-2).

Overall, the gait pattern tended to be more deviated in TM^+ compared to OG. The GPS was on average 0.81° higher in TM^+ for CP and 0.35° for TD (p=0.055; Table 10-1, Fig. 10-3). The difference between subjects was quite large: 5 out of 9 CP subjects walked slightly less deviated in TM^+ compared to OG (0.06-0.35° lower GPS score in TM^+), while 4 had a clearly higher score (0.62-4.39° higher score in TM^+). The MAP scores for knee and ankle flexion were significantly higher in TM^+ than OG (Fig. 10-3), indicating more deviation in these joints in TM^+.

As for the subjective scores, six TD subjects said they preferred TM^+ over OG, while five preferred OG. Seven children with CP preferred TM^+ over OG, while the other two had no preference. These general preferences were reflected in the subjective scores, which were lowest for OG and highest for NW (Table 10-1).

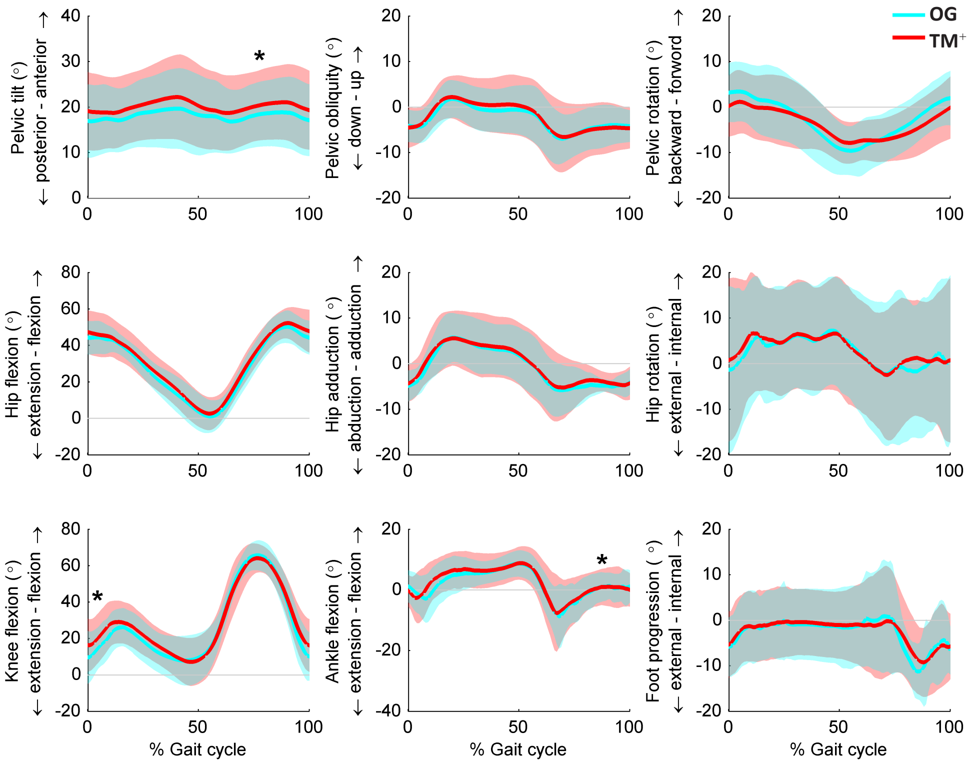

Fig 10-2B. Kinematic curves averaged over CP for conventional gait lab (OG, cyan) and self-paced treadmill walking in a virtual environment (TM^+, red), with standard deviation. Stars and arrows indicate a significant difference in key kinematic parameters (see Table 10-1).

Discussion

This study aimed to compare self-paced treadmill walking in a virtual environment to overground walking in a conventional gait lab and to natural walking outside a lab environment. Subjects walked slower and with shorter strides in both lab conditions compared to NW, while stride width was widest in TM^+ compared to both overground conditions. Mean kinematic curves were generally similar between OG and TM^+ for both groups, although children with CP walked with slightly more pelvic tilt, more knee flexion at initial contact, and in general more deviation in knee and ankle kinematics in TM^+.

Most differences in spatiotemporal parameters are in line with previous literature on treadmill walking. As in several other studies [13,25], subjects took shorter and wider strides on the treadmill compared to overground. Similar to Vogt *et al* [3], subjects selected a similar cadence as overground. The 3-4 cm wider steps on the treadmill can likely be attributed to the split belt, as Altman *et al* [25] found that stride width increased by 3.7 cm on a split-belt compared to a single-belt treadmill. Surprisingly, subjects did not walk significantly slower in TM^+ compared to OG, but slower in both labs compared to NW. Not many studies have compared walking speed inside and outside

Table 10-1 Outcome parameters

Parameter	**TD**			**CP**			**CP vs TD**			
	OG	TM⁺	NW	OG	TM⁺	NW	CON	BONF	GRP	INTR
	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	*p*		*p*	*p*
Subjective score	8.3±1.3	8.6±1.0	9.1±0.9	7.4±2.9	8.3±1.8	9.1±1.1	0.021	OG-NW	0.685	0.574
Walking speed (m/s)	1.34±0.18	1.30±0.28	1.42±0.14	1.14±0.20	1.03±0.30	1.21±0.17	0.023	NW	0.013	0.650
Cadence (steps/s)	1.97±0.25	1.97±0.26	2.02±0.18	1.85±0.18	1.86±0.20	1.90±0.12	0.281		0.171	0.985
Stride width (cm)	7.70±1.84	10.57±3.37	7.50±2.40	10.03±3.02	13.79±4.64	9.67±2.92	0.000	TM⁺	0.040	0.655
Stride length (m)	1.36±0.10	1.32±0.20	1.41±0.10	1.24±0.21	1.11±0.28	1.27±0.18	0.003	NW	0.052	0.305
Stance (%)	64.20±1.36	64.77±1.47	56.51±1.38	64.87±2.24	65.48±2.88	56.12±1.76	0.000	NW	0.635	0.357
Foot progression (°)	-2.38±4.09	-3.87±6.03	-1.92±4.22	-1.52±7.79	-1.23±7.52	-1.95±9.25	0.746		0.342	0.680
Mean pelvic tilt (°)	10.25±5.37	10.35±4.81		18.14±7.54	20.12±8.20		0.041		0.007	0.061
Range pelvic tilt (°)	5.18±1.32	5.33±1.28		7.68±2.77	7.00±1.61		0.363		0.013	0.153
Mean pelvic rotation (°)	0.28±0.31	0.09±0.19		-2.92±5.30	-3.64±5.00		0.260		0.033	0.513
Min hip flexion (°)	-8.49±5.95	-8.18±5.34		0.41±8.86	2.02±8.73		0.305		0.007	0.489
Range hip flexion (°)	50.02±4.75	50.26±5.44		50.95±8.23	51.70±7.00		0.733		0.638	0.864
Peak hip abduction swing (°)	-5.82±2.03	-6.59±2.38		-8.77±2.87	-8.44±4.03		0.623		0.062	0.224
Mean hip rotation stance (°)	0.04±6.15	-0.75±5.84		4.14±12.73	4.61±12.18		0.787		0.275	0.277
Knee flexion at IC (°)	-1.66±3.02	-1.34±3.14		9.60±14.54	16.38±14.55		0.001		0.004	0.002
Time to peak knee flexion (°)	75.38±1.39	76.14±1.58		77.20±3.28	77.18±3.36		0.307		0.193	0.283
Range knee flexion (°)	77.26±5.40	77.73±4.55		64.76±15.87	61.53±14.61		0.135		0.008	0.051
Peak ankle dorsiflexion stance (°)	10.06±5.69	10.23±5.82		10.85±4.28	9.95±5.64		0.599		0.917	0.442
Peak ankle dorsiflexion swing (°)	4.76±4.38	2.36±5.34		4.46±5.68	2.45±5.95		0.020		0.964	0.825
Gait Profile Score (°)	4.42±0.83	4.77±0.89		9.30±2.39	10.11±3.16		0.055		0.000	0.421

Abbreviations: TD: typically developing; CP: cerebral palsy; CON: conditions, *i.e.* OG, TM⁺: NW; BONF: results of the post hoc test with Bonferroni adjustment. OG–NW means a significant difference between OG and NW; NW or TM⁺ means a significant difference between NW/TM⁺ and the other two conditions, GRP the difference between TD and CP; INTR the interaction effect between CON and GRP.

a gait lab. Najafi *et al* [26] found that walking speed increased by 15% and 3%, when increasing the walkway from 7 to 14m and from 14 to 20m respectively. This may explain the slower speed on the 10m walkway in our OG compared to the courtyard, and indicates that a long enough walkway is needed to obtain natural walking speed. The similar speed between TM+ and OG, especially in TD subjects, contrasts with most studies showing slower speed on a treadmill [3,11]. This may be a coincidence resulting from our small sample size but it may also be thanks to an improved reality experience resulting from the SP mode and the large screen projecting optical flow

The increased deviation found in knee and ankle kinematics on the treadmill in CP may be attributable to increased fatigue in TM+. Due to habituation and the number or trials, total walking time was considerably longer in TM+ than in OG. Furthermore, we found in some subjects that the gait deviations increased in TM+ throughout the protocol. The GPS and MAP scores remained relatively constant when CP subjects in TM+ were compared against TD subjects walking also in TM+ (rather than TD subjects in OG as presented in the results section), indicating that the gait deviations were truly due to CP and not systematic for TM+. The decreased knee extension at IC in TM+ may also be related to shortened stride length. The only significant kinematic change between the two lab modes in both TD and CP subjects was increased ankle dorsiflexion in swing. This was in line with Sheik-Nainar *et al* [14], who found approximately 4° lower ankle dorsiflexion at initial contact during treadmill compared to overground walking, and may be attributed to the more compliant walking surface on the treadmill.

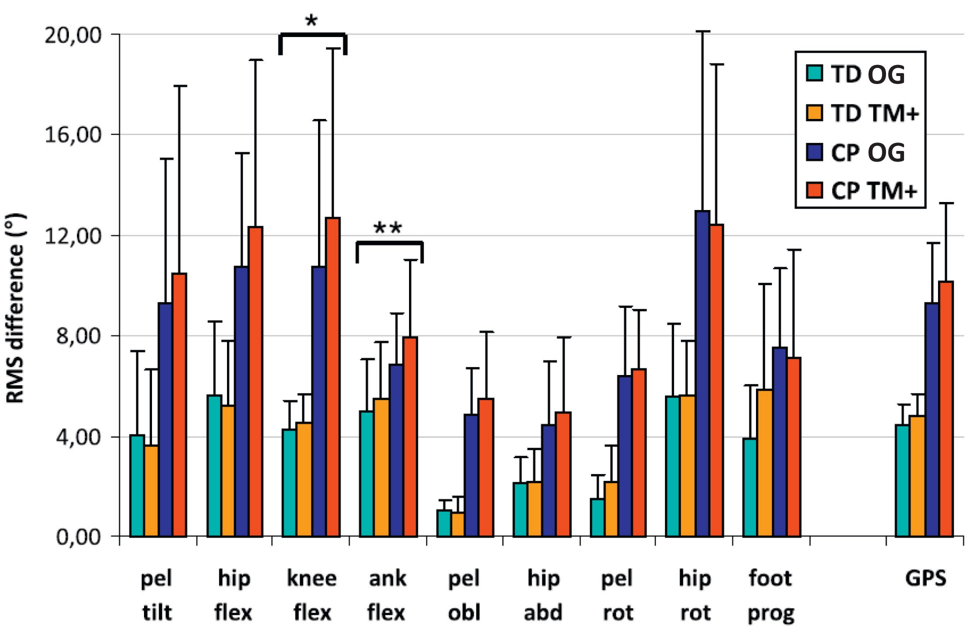

Fig 10-3. Movement Analysis Profile (MAP) and Gait Profile Scores (GPS). All values are relative to the mean of TD conventional gait lab (OG). Stars indicate a significant difference between OG and TM+ (* p<0.05, ** p<0.01). TD: typically developing; CP: cerebral palsy; OG: conventional gait lab; TM+: self-paced treadmill walking in a virtual environment.

Some of the differences between OG and TM^+ can be considered clinically relevant for individual patients. Two out of nine CP subjects had an increase in GPS score in TM^+ of more than 1.6°, which is considered a clinically relevant change [27]. On the other hand, the GPS was slightly lower in TM^+ in 5 out of 9 CP subjects, indicating that these subjects walked as well in TM^+ as in OG. The significant kinematic differences exceeded the intra-subject stride-to-stride variation as quantified by the SD: for mean pelvic tilt this intra-subject SD was 1.0±0.5° while the average difference between labs was 2.0° (Table 10-1). For knee flexion at IC the intra-subject SD was 3.2±2.1°, and the difference between labs was 6.8°. In 4 out of 9 CP patient, the difference in knee angle at IC exceeded 5°, which is often considered a clinically relevant difference [28]. The average RMS difference between labs (2.4° for TD; 3.4° for CP; Table 10-2) was higher than the intra-subject SD (2.0±0.5° for TD; 2.6±0.7° for CP). Furthermore, individual differences ranged up to 10.1° for hip flexion and 13.8° for knee flexion in one of the CP patients (Table 10-2), clearly representing a clinically relevant effect. These findings indicate that some of the differences between labs need to be taken into account, especially for CP.

However, differences between labs do not necessarily mean that treadmill walking is less suitable for clinical gait analysis. The wider and shorter steps in TM^+ seem to be a systematic difference with CGA. This can be accounted for by using a good TM^+ specific reference data set, and likely does not influence the sensitivity of the gait analysis to identify treatment effects. The fact that gait deviations tend to be enhanced in TM^+ can be considered an advantage when the clinical question is to search for causes of these deviations. In line with this, some parents remarked that the gait pattern in TM^+ better resembled every-day walking than OG, but this needs further investigation. As stated above, fatigue seems to play an important role, and is also a relevant factor in every-day walking in children with CP [29]. Self-paced treadmill walking could therefore become a powerful tool to study fatigue effects in CP and other patient populations. It is important though to use standardized protocols balancing the amount of fatigue with enough habituation time.

Table 10-2. Root mean square errors (RMSE) between OG and TM^+

Parameter	**TD RMSE (°)**		**CP RMSE (°)**	
	Mean±SD	Range	Mean±SD	Range
Pelvic tilt	1.77±1.17	0.44-4.48	2.56±1.67	1.10-6.30
Pelvic obliquity	0.71±0.20	0.33-1.07	1.83±1.35	0.70-5.27
Pelvic rotation	2.18±1.34	1.23-4.80	3.77±1.23	2.67-6.18
Hip flexion	3.13±1.85	1.54-7.64	3.95±2.72	2.01-10.1
Hip adduction	1.58±0.77	0.65-3.02	2.08±0.90	0.90-3.81
Hip rotation	2.53±1.22	0.94-4.57	3.45±1.74	1.54-7.53
Knee flexion	2.99±1.21	1.69-5.23	5.42±3.91	2.26-13.8
Ankle flexion	2.78±1.23	1.23-5.87	3.79±2.00	1.25-6.24
Foot progression	3.81±2.14	1.35-7.36	3.76±1.74	1.22-6.76
Mean	2.39±1.24	1.04-4.89	3.40±1.92	1.52-7.33

Abbreviations: TD: typically developing; CP: cerebral palsy.

Several limitations need to be taken into account when interpreting our results. First, we evaluated kinematics only and excluded kinetics from our analysis. We focused on kinematics since this most directly displays how subjects alter their gait pattern, while kinetics could be more contaminated by reduced accuracy of treadmill compared to overground force plates. However, in order to decide whether treadmill walking is a complete alternative for overground clinical gait analysis, kinetics need to be taken into account as well. Second, we did not study the individual effects of VR and SP mode in CP, which are known to have a small effect on gait parameters in healthy adults [1,30]. This is subject of further study. Third, only a small sample of CP subjects was included and variability between subjects was large, thereby limiting the power of the study. Some differences, such as differences in walking speed and stride length between TM^+ and OG, may become significant with a larger group of subjects. Finally, all patients included in the study were relatively good walkers, as our inclusion criterion was that subjects had to be able to walk independently for at least 5 min on end. Further investigation of treadmill walking in CP with more subjects, including individuals with more severe gait limitations, is needed to show the feasibility of the system for the entire spectrum of ambulant CP patients.

Conclusion

We found that differences between self-paced treadmill walking in a virtual environment (TM^+) and overground walking in a OG are generally small and non-significant in children with and without CP. However, stride width in all subjects, and knee and ankle kinematics in CP were found to be systematically different and may be clinically relevant in individual cases. Walking speed in both labs was slower than natural walking (NW) speed. These differences should be taken into account when performing clinical gait analysis on a treadmill.

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