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Full length article

How normal is normal: Consequences of stride to stride variability, treadmill walking and age when using normative paediatric gait data

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ABSTRACT

Background: In the process of 3D-gait analysis interpretation, gait deviations in children with cerebral palsy are identified through comparison with reference data of typically developing children (TD). Generally, TD-data are presented based on averaged normalized curves of numerous strides for different ages and walking velocities. In patients however, often only a limited number of strides are available which are compared to group-averaged reference curves.

Research question: To investigate the consequences of ignoring stride-to-stride variation when averaged normalized curves are used as a reference paediatric dataset. To illustrate implications for clinical practice, we investigated how many individual strides of TD-children would be classified as abnormal, when compared to averaged normalized curves from the reference group, and how this is affected by age and treadmill versus overground walking.

Methods: Ninety TD-datasets were collected. Children (4-18y) walked on a 10 m-walkway ($n = 49$) or instrumented treadmill ($n = 41$). Joint kinematic and kinetic curves and clinically relevant outcome parameters were established. Individual strides were considered abnormal if they exceeded the group average more than 2SD. In addition, the Edinburgh Visual Gait Score, Gait Profile Score (GPS) and stride-to-stride variability were calculated. Generalized estimation equation analyses were used to investigate effects of age, overground/treadmill and their interaction.

Results: Of all 2532 analysed strides, on average 28% were classified as abnormal for joint kinematic curves, 50% for moments, and 51% for powers. Younger children showed a greater percentage of abnormal strides, greater GPS and more variability ($p < 0.001$). The effect of age was similar between treadmill and overground, but variability was lower on the treadmill.

Significance: Our findings indicate that due to stride-to-stride variability, even in TD-children a substantial number of strides can be classified as abnormal, when compared to group averaged normalized curves. Consequently, in patients, comparing a single stride to such a reference curve may lead to potential overestimation of gait deviations.

1. Introduction

Three dimensional clinical gait analysis is often performed in children with cerebral palsy (CP), to guide treatment decisions and improve surgical outcomes. In one aspect of this process, the measured gait function of children with CP is compared to a set of reference gait data of typically developing (TD) children. These reference datasets are often presented as grouped averages [1], for children across different ages and walking velocities, visualized as a grey band in the gait report representing the mean plus group standard deviation [1,2]. In clinical practice, a limited number of strides of a child with CP is collected for comparison to this reference dataset. Clinicians then use this to highlight pathological gait features that may fall outside the 'normal' walking curves [1–4]. Findings from gait analysis, along with clinical measures are combined, providing indications for intervention [1,4]. Overall gait function can be also quantified relative to this normative dataset, using scales such as the gait profile score (GPS) and gait deviation index (GDI) [5,6].

Although this process is accepted as standard clinical practice and described in methods such as the impairment focused approach to interpretation [1], some basic statistical assumptions are violated in this approach. First, reference curves are usually based on grouped averages; multiple strides are first averaged within an individual and then averaged across the group. Therefore, the variability presented by the grey band (i.e. plus and minus one or two standard

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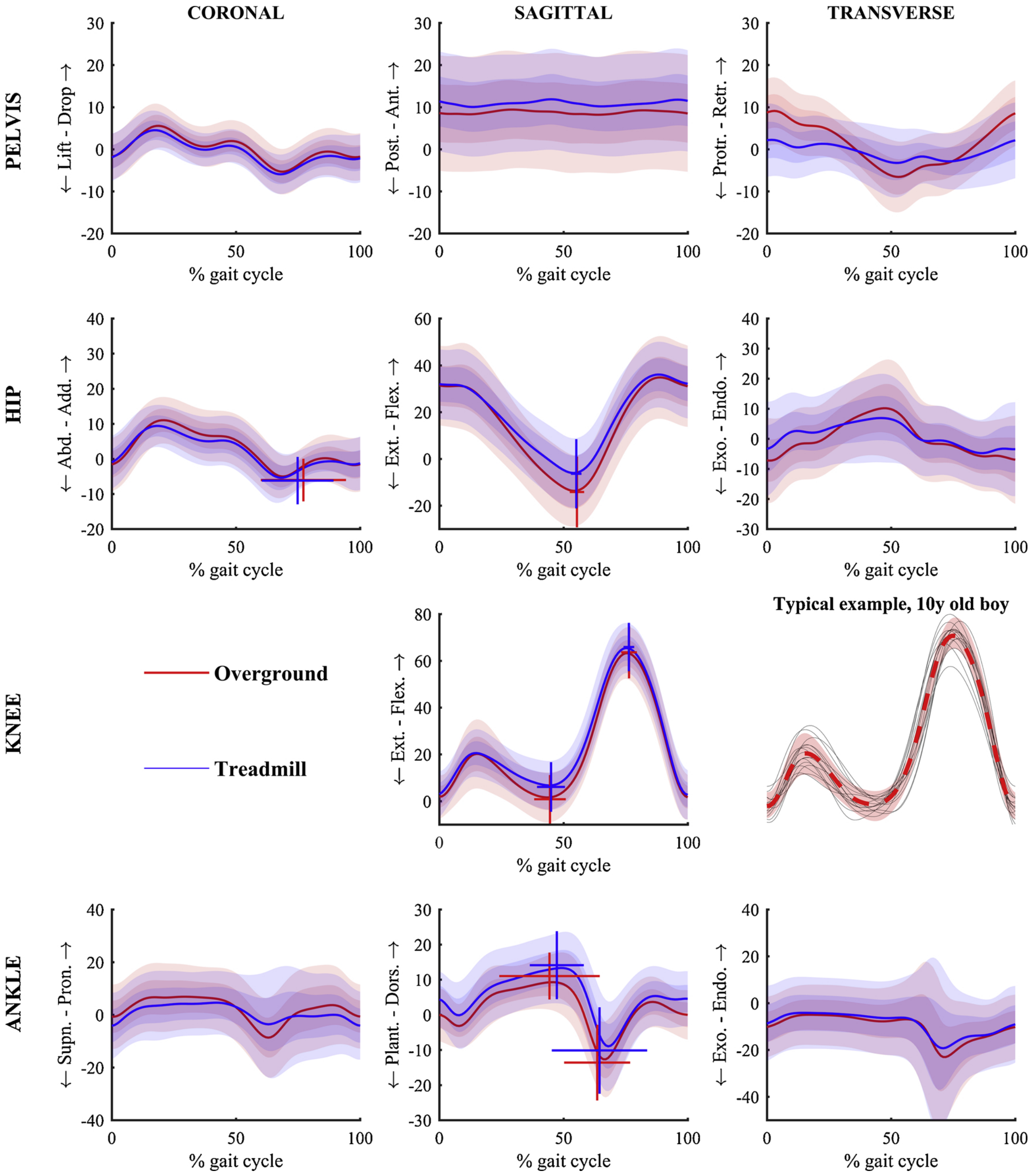

Fig. 1. Kinematic curves averaged over all typically developing children for the overground (red) and treadmill (blue) condition, with two standard deviations for each group (light shaded; darker colours indicate 1SD). Crosses indicate a selection of the clinically relevant outcome parameters (CROPS), i.e. peak values, with two standard deviations in amplitude (vertical) and timing (horizontal). As an example of inter-individual variation, individual strides of one boy are presented (thin black lines) as well as his individual averaged curve (dashed red line), while walking in the overground gait lab.

deviation) does not reflect variability of underlying individual strides, but variability between the averaged strides of subjects. As a consequence stride-to-stride variability within paediatric gait is masked by averaging over many strides. While several studies investigated effects of stride-to-stride variability in unimpaired adults and patient groups [7], little is known about these effects in children. Based on theories of motor development, it can be suggested that age is an important factor, since movements in younger children are more variable than in older individuals [8–11].

Secondly, one of the assumptions of averaging gait curves, after time normalizing to 0–100%, is that all variation is in the amplitudes, not in timing of gait events. Although this holds to some extent for kinematics while walking at a fixed velocity, walking speed has a strong effect on the timing of gait events [12,13]. Therefore, temporal misalignment of peaks is likely to occur [14,15]. Since walking speed is more variable in younger children [11], the consequences of this assumption may be exacerbated in younger children to a larger extent than in older children. In addition, it may play a bigger role for children walking in a conventional overground gait lab at a free walking speed, compared to walking on a treadmill, since treadmill walking allows for a more continuous walking pattern.

To address these issues, the aim of the present study is to investigate the consequences of ignoring stride-to-stride variation when averaged normalized curves are used as a reference paediatric dataset for individual strides, and how this is affected by age and treadmill versus overground walking. To illustrate the implications for clinical practice, we investigate how many individual strides of typically developing children do not match the group average. Alternatively defined, we investigate how many strides can be classified as ‘abnormal’ when compared to their own reference group. Due to stride-to-stride variability, we hypothesize this number of abnormal strides to be greater in younger children

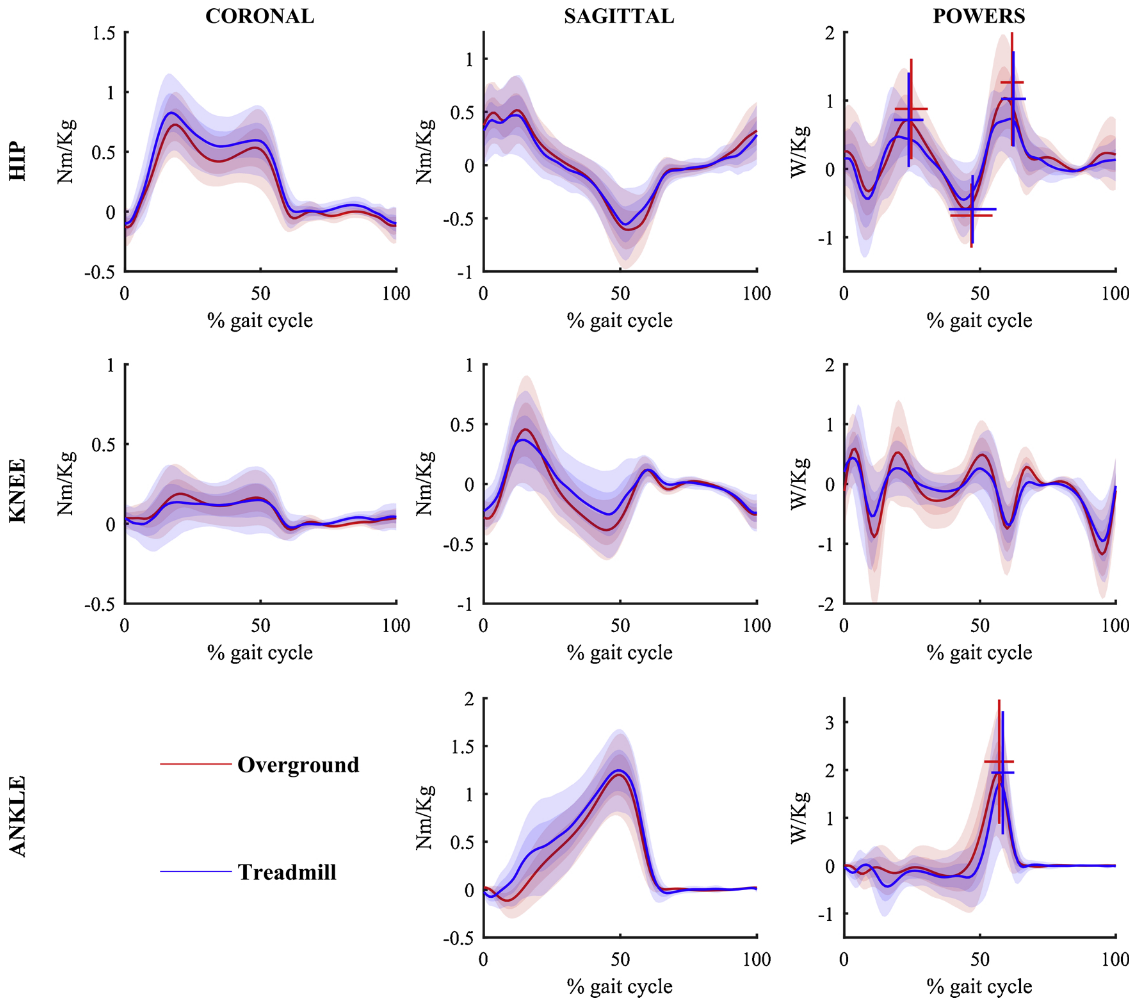

Fig. 2. Kinetic curves averaged over all typically developing children for the overground (red) and treadmill (blue) condition, with two standard deviations for each group (light shaded; darker colours indicate 1SD). Crosses indicate clinically relevant outcome parameters (CROPS), i.e. peak values, with two standards in amplitude (vertical) and timing (horizontal). Positive values indicate internal abduction (coronal plane) and extension/plantar flexion (sagittal plane).

and in overground walking. Since previous studies show that gait is highly affected by walking speed [12], effects of walking speed are also considered.

2. Methods

2.1. Participants

Ninety datasets were collected of TD children walking either in an overground gait lab or on a treadmill. Children were included if they were between 4–18 years of age and had no impairments or conditions that could interfere with walking ability. Exclusion criteria were any injuries, physical conditions or cognitive disabilities that might affect walking ability. Written informed consent was given by parents and children (if > 12 years) before the start of the experiment. The study was approved by the local ethics committees of the VU University Medical Centre and the VU University, both in line with the declaration of Helsinki.

2.2. Study design and materials

The overground gait laboratory consisted of a 10 m walkway with two embedded force plates (AMTI, Watertown, MA, USA). After familiarization, children were asked to walk up and down the walkway at a self-chosen comfortable walking speed. During the measurements, parents were asked to confirm whether children showed their typical daily life gait pattern. Measurements were continued until sufficient representative strides were collected, aiming for at least five force plate hits for each leg.

The treadmill laboratory consisted of a dual-belt instrumented treadmill with speed-matched virtual reality environment projected on a surrounded screen (Gait Real Time Analysis Interactive Laboratory (GRAIL) system, Motek Medical BV, Amsterdam, the Netherlands). After a familiarization period of at least 6 min, children walked at their self-chosen walking velocity. This was determined either by the child with a self-paced algorithm or using a fixed speed condition. In the latter case, the speed was increased until the children felt comfortable, at this stage the speed was increased until it was considered too fast for walking, speed was then reduced until the participants suggested it was their comfortable walking speed. The speed in the middle of the two speeds suggested as comfortable was taken as the self-selected walking speed and fixed throughout the rest of data collection, which was at least 1 min.

3D motion data was captured with passive retroreflective and infrared cameras (Vicon, Oxford UK) in both labs, following an updated version of the Human Body Model (HBM) [16,17]. Most relevant updates to the previous reported version of HBM concerned the knee and ankle axis, which are no longer pose dependent due to the use of medial markers, making it more robust for clinical use in patients. Data was processed using the Gait Offline Analysis Tool (version 4.0, Motek Medical B.V., Amsterdam, The Netherlands).

2.3. Data analysis

3D kinematic and kinetic data were analysed for the right leg only. Gait events were calculated according to Zeni [18]. Strides that were clear outliers (e.g. running, standing still, skipping) were manually excluded. Walking speed, stride length, and step length were non-dimensionalised through normalization to leg length (maximal distance ASIS to medial malleolus during the static trial), following the methods of Hof [19]. Both overground and treadmill data sets are shared in the supplementary material, as this paper may also serve as a paediatric reference base for HBM (16)).

To assess the normality of individual strides, four different approaches were used:

Method A: Kinematic and kinetic curves of individual strides were compared to the group averaged curves of the same parameter. Strides were considered 'abnormal', if individual strides of a child exceeded the group averaged curves by more than 2 SD (group SD) for more than 10% of the gait cycle.

Method B: A set of clinically relevant outcome parameters (CROPs) were extracted for individual strides of all children (see Table 2). Based on these CROPs, abnormal strides were identified as individual strides where CROPs exceeded the group averaged CROP by more than 2 SD (group SD) in either amplitude or timing.

Method C: As a measure for overall gait abnormality, the gait profile score (GPS) and Edinburgh Visual Gait Score (EVGS) were calculated. GPS was calculated using the root mean square (RMS) difference between gait kinematic curves for individual children, compared to the group average, following the methods described by Baker [5]. In addition to the GPS for kinematics, GPS was also calculated for joint moments and powers, using the same methods as applied for kinematics. As several video-based measures may have additional clinical relevance augmenting 3D kinematics, EVGS score was calculated for the overground data, based on deviations at clinically meaningful events of the gait cycle [20]. EVGS was assessed from frontal and sagittal videos, and averaged over both legs. All videos were analysed by the same experienced investigator, using custom-made video analysis software [21].

Method D: For spatiotemporal parameters, GPS and CROPs, the stride-to-stride variability was quantified as the SD between strides within each individual child.

2.4. Statistics

To assess the effect of age, condition (treadmill/overground), their interaction (age X condition) and non-dimensional walking speed on all outcome measures, linear generalized estimation equation (GEE) analyses were performed. This method was chosen, as it can correct for differences of walking speed between children and between the conditions. For each outcome parameter evaluated, an individual linear equation was evaluated, with β-values representing coefficients of the individual regression terms and p-values evaluating whether terms contributed significantly to the constructed equation. Due to the large number of parameters evaluated, significance level was set at $p < 0.01$. The term correcting for non-dimensional walking speed was included only if it was significant at $p < 0.05$. In addition, independent sample t-tests were performed to compare participant characteristics between both conditions, with a significance level of $p < 0.05$.

3. Results

Data of 49 children (28 girls, 21 boys) were included for the overground 3D gait analyses and of 48 children for 2D video analysis. Data were excluded due to a lack of complete video recordings (n = 2, excluded from video analysis only) and absence of kinetic data (n = 1, excluded from all

Table 1

Percentage of abnormal strides based on individual gait curves exceeding 2-SD during &10% of the gait cycle (method A). Mean/SD represent group average, expressed as the ratio between the number of abnormal strides of an individual and his/her number of strides analyzed. Evaluated results in GEE concern the effect of age, condition (treadmill/overground), their interaction, and walking speed on percentage of abnormal strides. GEE according to: percentage abnormal strides= $\beta_1 + (\beta_2 * \text{age}) + \beta_3 * (\text{condition}) + \beta_4 * (\text{age X condition})\ \beta_5 * (\text{non-dimensional walking speed})$. Condition was entered as a categorical variable: treadmill =1, overground =0. Individual strides were classified abnormal if curves exceeded group mean +/- 2SD for > 10% of the gait cycle (method A). Note that non-dimensional walking speed was only included if it contributed significantly to the regression formula ($p < 0.05$). Results significant at $p < 0.01$.

	Mean/SD	**Intercept**	**Age effect**		**Condition effect TM^1/OG^0**		**Age x Condition**		**walking speed effect**	
Outcome measure		B_1	B_2	p	B_3	p	B_4	p	B_5	p
Kinematics										
Pelvis										
Tilt (% abnormal)	10 ± 22	**23.9**	-1.5	0.011	7.5	0.632	-0.8	0.51		
Obliquity (% abnormal)	28 ± 31	**55.6**	**-3.0**	**0.006**	-8.8	0.678	1.2	0.55		
Rotation (% abnormal)	41 ± 27	**73.6**	**-3.1**	**0.001**	-6.2	0.698	0.2	0.91		
Hip										
Flex-ext (% abnormal)	14 ± 23	**38.9**	**-2.6**	**<0.001**	9.1	0.604	-0.8	0.58		
Abd-Add (% abnormal)	26 ± 30	**110.2**	**-3.4**	**0.001**	-3.2	0.864	-0.8	0.63	**-107.6**	**0.007**
Rotation (% abnormal)	24 ± 27	**47.1**	-2.0	0.012	2.5	0.877	-1.0	0.45		
Knee										
Flex-ext (% abnormal)	33 ± 31	**84.0**	**-5.0**	**<0.001**	-17.7	0.330	1.3	0.45		
Ankle										
Plflx-dflx (% abnormal)	28 ± 31	**51.4**	-2.0	0.111	-15.7	0.414	0.6	0.76		
Kinetics										
Moments										
Hip										
Flex-ext (% abnormal)	50 ± 34	-64.4	1.0	0.526	44.1	0.039	-1.3	0.50	**213.5**	**<0.001**
AbAdd (% abnormal)	55 ± 30	**-66.6**	**3.2**	**0.005**	35.7	0.052	-1.6	0.36	**189.8**	**<0.001**
Rot (% abnormal)	60 ± 31	-41.3	0.4	0.726	**48.3**	**0.002**	-0.4	0.80	**183.2**	**<0.001**
Knee										
Flex-ext(% abnormal)	57 ± 34	-31.3	-0.3	0.858	37.0	0.086	-0.2	0.91	**177.4**	**<0.001**
AbAdd (% abnormal)	53 ± 30	**-78.7**	2.2	0.066	**51.7**	**0.003**	-1.7	0.34	**221.1**	**<0.001**
Rot (% abnormal)	64 ± 29	-35.8	-0.3	0.748	**46.2**	**<0.001**	0.1	0.91	**192.4**	**<0.001**
Ankle										
Plflx-dflx (% abnormal)	54 ± 34	-28.8	-0.8	0.520	43.0	0.033	-0.2	0.94	**170.0**	**<0.001**
Powers										
Hip (% abnormal)	55 ± 35	**-110.8**	-1.0	0.337	**39.5**	**0.007**	0.2	0.90	**367.1**	**<0.001**
Knee (% abnormal)	56 ± 36	**-69.4**	-1.8	0.101	34.0	0.053	0.9	0.60	**289.1**	**<0.001**
Ankle % abnormal	53 ± 35	-47.0	**-3.5**	**<0.001**	38.7	0.017	1.1	0.48	**262.6**	**<0.001**

Bold numbers indicate significant effects ($p < 0.01$).

analyses). Forty-one datasets (17 girls, 24 boys) were collected on the treadmill, data of three children were excluded from kinetic analysis due to hardware issues. For individuals walking overground, for kinematics, on average 17 strides were included (min 10; max 38), whereas for kinetics on average 6 strides were included for analysis [1–12]. For treadmill walking, for kinematics on average 34 were included (min:11, max 54), whereas for kinetics on average 27 strides were included (min: 11, max 44). No differences were found between the overground and treadmill group for participants' age or mass (overground: mean age 9.6y, range 4–17; mass 36.8 ± 16 kg vs. treadmill: mean age 10y, range 5–15; mass 40.1 ± 13.2 kg). However, children in the treadmill group were slightly taller (overground: 1.38 ± 0.21 m vs. treadmill: 1.48 ± 0.19 m; $p = .044$) and absolute as well as non-dimensional comfortable walking speed were slower on the treadmill compared to overground walking (overground: 1.22 ± 0.14 m/s vs. treadmill: 1.05 ± 0.20 m/s; $p < 0.01$).

Kinematic, kinetic and CROP data are presented in Figs. 1 & 2 and Tables 1 & 2 . Complete results, kinematics/kinetics curves, and spatiotemporal parameters are available in the supplementary material.

For method A, on average 28% were classified as abnormal for joint kinematic curves, 50% for moments, and 51% for powers, as a mean of the different joints. The least strides were classified as abnormal for pelvic tilt (9%) and most for hip rotation (41%) (Table 1). For joint moments, least strides were classified as abnormal for hip flexion moments (43%) and most for hip rotational moments (59%). For joint powers, least strides were classified as abnormal for hip power (49%) and most for ankle power (53%).

For most kinematic curves, significant effects were found for age on the number of abnormal strides, where younger children showed a greater percentage of abnormal strides (Table 1). For kinetics, the number of abnormal strides was related to walking speed for most parameters, where more abnormal strides were classified for faster walking speeds. Overall, the number of abnormal strides was greater on the treadmill than overground for some kinetic parameters. No interaction effects were found between condition and age for both kinematic and kinetic curves.

For method B, the number of strides classified abnormal based on CROPs was on average 15% for kinematics. The least number of abnormal strides were found for pelvis tilt (5%) and most for peak hip abduction in swing phase (24%). For kinetics, on average 15% of strides were classified abnormal, where least abnormal strides were classified for peak ankle plantarflexion moment (6%) and most for peak hip moments (23%) (Table 2). The number of abnormal strides based on CROPs was related to children's age for most parameters, even after correction for non-dimensional walking speed, again with more abnormal strides for younger children. For kinetics, effects were mainly related to non-dimensional walking speed. For most outcome parameters, no difference was found between overground and treadmill walking (Table 1,2, Figs. 1–3).

Concerning method C, mean GPS score was 6.4° for kinematics (Table 2). Alternative GPS scores calculated for kinetics were 0.12 Nm/kg for joint moments and 0.35 J/kg for powers. Mean EVGS was 1.7 (only calculated for children who walked in the overground condition). GPS was significantly related to age, where older children showed lower GPS scores (fewer deviations) ($p < 0.001$, Fig. 3). These effects were similar between overground and treadmill walking and not affected by walking speed. A comparable trend of a decrease with age was found for the EVGS, although this did not reach significance ($p = 0.023$).

Stride-to-stride variability (method D), expressed by children's individual SD, decreased with age, where younger children presented greater SDs for most parameters (Table 2). Overall, stride-to-stride variability was greater for overground compared to treadmill walking for most outcome

Table 2

Mean values and results of GEE analysis for clinically relevant outcome parameters (CROPS). Outcome measures presented in the first column represent: CROP – parameters, individual standard deviations (within-subject SD) and percentage number of abnormal strides for individuals, based on values exceeding the group value +/− 2 SD (method B). Evaluated results in GEE concern the effect of age, condition (treadmill/overground) as well as their interaction, where B-values represent coefficients for each of these parameters. Note that non-dimensional walking speed was only included if it contributed significantly to the regression formula ($p < 0.05$). GEE according to: outcome = β1 + (β2*age) + β3*(condition) + β4*(age X condition) β5*(non-dimensional walking speed).

	Mean/SD	**Intercept**	**Age effect**		**Condition effect TM^1/OG^0**		**Age x Condition**		**walking speed effect**	
Outcome measure		B$_1$	B$_2$	p	B$_3$	p	B$_4$	P	B$_5$	p
Spatiotemporal										
Walking speed (m/s)	1.2 ± 0.2	**1.01**	**0.02**	**0.004**	-0.17	0.165	0.00	0.988	n.a.	n.a.
ND walking speed	1.2 ± 0.2	**0.50**	0.00	0.021	-0.07	0.135	0.00	0.948	n.a.	n.a.
Stance/swing (%)	65 ± 1	**69.17**	0.02	0.417	0.50	0.236	-0.03	0.483	**-11.20**	**<0.001**
SD	1.1 ± 0.3	**1.82**	**-0.07**	**<0.001**	-0.16	0.364	0.02	0.144		
Stance time (s)	0.63 ± 0.09	**0.85**	**0.01**	**<0.001**	-0.01	0.737	0.00	0.591	**-0.72**	**<0.001**
SD	0.03 ± 0.01	**0.06**	**0.00**	**<0.001**	-0.02	0.026	0.00	0.148		
Overall gait score										
GPS (°)	6 ± 2	**8.50**	**-0.20**	**<0.001**	0.61	0.421	-0.09	0.251		
SD	0.9 ± 0.5	**1.91**	**-0.10**	**<0.001**	-0.53	0.007	0.03	0.045		
GPS moments	0.12 ± 0.02	**0.09**	0.00	0.854	0.03	0.042	0.00	0.509	0.06	0.047
SD	0.02 ± 0.01	**0.03**	0.00	0.469	0.00	0.984	0.00	0.267		
GPS powers	0.35 ± 0.09	0.10	**-0.01**	**0.003**	0.01	0.912	0.00	0.469	**0.73**	**<0.001**
SD	0.35 ± 0.09	0.04	**-0.01**	**0.001**	-0.03	0.268	0.00	0.381	**0.19**	**<0.001**
EVGS	1.7 ± 1.3	**2.64**	-0.10	0.023	n.a.	n.a.	n.a.	n.a.		
Kinematics										
Pelvis										
Mean tilt (°)	10 ± 7	**11.86**	-0.32	0.166	3712.00	0.350	-0.14	0.690		
SD	2 ± 1	**4.49**	**-0.26**	**<0.001**	**-1.63**	**0.005**	0.13	0.010		
% abnormal**	5 ± 18	11.07	-0.72	0.025	9.20	0.468	-0.72	0.441		

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Table 2 *(continued)*

Hip										
Minimal flexion (°)	-11 ± 8	-1.36	-0.13	0.606	10.14	0.037	-0.40	0.356	-24.98	0.024
SD	2 ± 1	**5.01**	**-0.25**	**<0.001**	-0.84	0.190	0.06	0.303		
% abnormal	18 ± 20	**39.37**	**-2.25**	**0.001**	5.58	0.629	-0.39	0.707		
Peak abd swing(°)	1 ± 3	-0.27	0.15	0.198	-1.36	0.545	0.06	0.761		
SD	2 ± 1	**3.16**	**-0.15**	**<0.001**	-0.33	0.321	0.04	0.226		
% abnormal	24 ± 28	**45.94**	-1.88	0.154	-8.60	0.655	-0.01	0.996		
Knee										
Flexion at ic (°)	8 ± 5	**12.95**	**-0.65**	**<0.001**	-5.19	0.096	**0.77**	**0.008**		
SD	3 ± 2	**6.92**	**-0.36**	**<0.001**	**-2.32**	**<0.001**	**0.16**	**0.006**		
% abnormal	10 ± 18	17.74	-0.63	0.561	4.65	0.561	-0.69	0.595		
Peak flexion stance (°)	38 ± 6	**38.92**	**-0.39**	**0.001**	8.52	0.018	-0.15	0.649		
SD	3 ± 1	**5.03**	**-0.18**	**0.000**	-0.54	0.348	0.03	0.552		
% abnormal	14 ± 22	**47.32**	**-3.03**	**<0.001**	**-36.70**	**0.007**	2.80	0.021		
Peak ext stance (°)	0 ± 5	0.17	-0.22	0.134	1.582	0.660	0.18	0.580		
SD	3 ± 1	**5.23**	**-0.26**	**<0.001**	-0.84	0.176	0.04	0.422		
% abnormal	17 ± 23	**30.12**	**-2.06**	**<0.001**	-10.39	0.513	2.93	0.066		
Peak flexion swing (°)	65 ± 5	**59.04**	**-0.69**	**<0.001**	6.62	0.016	-0.22	0.398	**24.30**	**0.001**
SD	3 ± 2	**5.81**	**-0.20**	**0.001**	**-2.46**	**<0.001**	0.08	0.213		
% abnormal	15 ± 22	**33.98**	**-1.96**	**<0.001**	-21.83	0.275	2.16	0.253		
Range of motion (°)	66 ± 6	**53.77**	-0.45	0.010	7.05	0.042	-0.52	0.102	**36.77**	**<0.001**
SD	3 ± 2	**6.76**	**-0.28**	**<0.001**	**-2.65**	**<0.001**	0.11	0.364		
% abnormal	15 ± 22	**17.90**	**-0.97**	**0.006**	-4.47	0.575	0.21	0.754		
Ankle										
Peak dflx stance (°)	12 ± 4	**9.83**	0.12	0.449	6.91	0.023	-0.37	0.199		
SD	2 ± 1	**3.06**	**-0.14**	**0.000**	-0.45	0.283	0.04	0.321		
% abnormal	21 ± 27	**50.97**	-2.80	0.014	-25.76	0.126	1.99	0.208		
Peak dflx swing (°)	5 ± 4	**3.76**	0.06	0.634	3.59	0.180	-0.13	0.610		
SD	2 ± 1	**2.88**	**-0.11**	**<0.001**	-0.46	0.191	0.01	0.655		
% abnormal	15 ± 26	9.81	1.07	0.382	10.52	0.588	-2.09	0.264		
Foot										
Mean progression (°)	-6 ± 7	-4.43	-0.19	0.344	9.13	0.330	-0.78	0.043		
SD	3,4 ± 1,2	**5.47**	**-0.19**	**<0.001**	-0.35	0.557	0.00	0.986		
% abnormal	7 ± 15	**15.10**	-0.76	0.036	1.38	0.872	-0.22	0.751		

(continued on next page)

Table 2 *(continued)*

Kinetics										
Moments										
Hip										
Peak extension (Nm/kg)	1 ± 0	**-0.39**	**0.02**	**<0.001**	0.18	0.060	-0.01	0.239	**1.86**	**<0.001**
SD	0.1 ± 0.1	-0.07	0.00	0.199	-0.01	0.901	0.00	0.849	**0.21**	**<0.001**
% abnormal	23 ± 22	**37.20**	-0.85	0.373	0.00	1.000	-1.30	0.329		
Peak hip flexion (Nm/kg)	-1 ± 0	0.01	**-0.03**	**<0.001**	0.02	0.805	**0.00**	**0.815**	**-0.88**	**<0.001**
SD	0.1 ± 0.0	**0.11**	0.00	0.611	0.02	0.421	0.00	0.361		
% abnormal	9 ± 19	-3.68	1.36	0.218	-7.17	0.575	0.44	0.772		
Knee										
Peak ext (Nm/kg)	0.5 ± 0.2	0.24	0.00	0.724	-0.32	0.011	0.03	0.011	0.61	0.022
SD	0.1 ± 0.1	0.08	-0.01	0.158	-0.09	0.027	0.01	0.063	**0.26**	**<0.001**
% abnormal	17 ± 23	-7.70	-0.63	0.608	-11.60	0.494	1.44	0.396	69.13	0.015
Mean ext (Nm/kg)	0.0 ± 0.1	0.18	-0.01	0.242	-0.06	0.429	**0.01**	0.199	**-0.40**	**0.006**
SD	0.1 ± 0.0	**0.09**	**0.00**	**0.005**	-0.04	0.019	0.00	0.071		
% abnormal	17 ± 23	-7.70	-0.63	0.608	-11.60	0.494	1.44	0.396	69.13	0.015
Peak abd (Nm/kg)	0.2 ± 0.1	**0.16**	**0.01**	**0.002**	-0.01	0.886	0.00	0.858		
SD	0.1 ± 0.0	**0.05**	0.00	0.023	-0.02	0.020	0.00	0.018	0.05	0.020
% abnormal	17 ± 23	-7.70	-0.63	0.608	-11.60	0.494	1.44	0.396	69.13	0.015
Ankle										
Peak pflx (Nm/kg)	1.3 ± 0.2	0.30	**0.05**	**<0.001**	**0.22**	**0.006**	-0.01	0.165	**0.97**	**<0.001**
SD	0.1 ± 0.1	**0.14**	0.00	0.467	-0.04	0.253	0.00	0.791		
% abnormal	6 ± 16	0.13	0.55	0.512	9.36	0.461	-0.77	0.558		
Powers										
Peak hip (W/kg)	1.3 ± 0.4	-0.33	-0.02	0.226	-0.31	0.102	0.03	0.033	**3.99**	**<0.001**
SD	0.3 ± 0.2	0.26	**-0.03**	**<0.001**	**-0.34**	**0.003**	**0.03**	**<0.001**	**0.92**	**<0.001**
% abnormal	16 ± 21	**45.02**	**-2.49**	**0.004**	**-34.92**	**0.003**	2.41	0.025		
Peak knee (W/kg)	0.9 ± 0.4	-0.42	-0.01	0.315	0.25	0.492	-0.01	0.674	3.26	**<0.001**
SD	0.3 ± 0.2	0.22	**-0.02**	**<0.001**	0.07	0.687	-0.01	0.732	**0.64**	**0.002**
% abnormal	22 ± 23	**37.45**		**0.006**	7.23	0.637	0.26	0.860		
Peak ankle (W/kg)	2.1 ± 0.7	-1.28	**0.13**	**<0.001**	0.76	0.041	-0.07	0.039	**4.81**	**<0.001**
SD	0.4 ± 0.2	0.05	-0.01	0.308	0.13	0.287	-0.01	0.350	**0.87**	**<0.001**
% abnormal	9.1 ± 18.8	19.16	-0.99	0.316	-19.51	0.155	1.85	0.171		

Condition was entered as a categorical variable: treadmill = 1, overground = 0. Results significant at $p < 0.01$. Bold numbers indicate significant effects ($p < 0.01$).

[**] Percentage of abnormal strides for pelvis tilt is not reported, since only 1 individual presented abnormal strides > 0.

parameters, including SD of GPS (p = 0.007, Fig. 3). Effects of age were comparable between overground/treadmill walking for most parameters, as indicated by the non-significant interaction effects between age and condition (Table 2).

4. Discussion

In common clinical gait analysis, individual strides of a patients gait are compared to a reference curves of typically developing children or normal adults. However, these references are based on averaged strides. The aim of the present study was to investigate the impact of ignoring this stride-to-stride variation when averaged normalized curves are used as a reference paediatric dataset, and how this is affected by age and treadmill versus overground walking. To illustrate the implications for clinical practice, we investigated how many individual strides of typically developing children could be classified as abnormal, when compared to their own reference group. For individual joints, 28% were classified as abnormal for joint kinematic curves, 50% for moments, and 51% for powers. This number demonstrates that considerable stride–to–stride variability is present in normal gait, and that the common interpretation scheme may lead to an unrealistically high number of abnormal strides.

The overall number of abnormal strides was greater when individual curves were compared to averaged group curves (method A), than if peak values (CROPs) were compared to group peak values (method B). This was more evident for joint moments and powers. This can be expected due to the larger impulse of kinetic curves, such as ankle power. Consequently, small deviations in timing leads to underestimation of the true peak value when curves are averaged. This phenomena has been described before as temporal misalignment of curves [14]. Effects are visible in Fig. 2, where the peak ankle power as indicated by the cross (CROP mean + SD in timing/magnitude) is much higher than the peak of the group averaged curve. This temporal misalignment may have consequences for interpretation of clinical gait analysis, where curves of individual strides are often compared to reference curves. If the parameter of interest is a discrete kinetic value such as peak ankle push-off power, comparing peak values to this averaged curve can lead to an incorrect estimation of deviations.

Younger children showed a greater percentage of abnormal strides with larger stride-to-stride variability than older children, on all outcome measures. Although comparable effects have been reported for spatiotemporal parameters [10,11], to our knowledge, no studies investigated effects of age on stride-to-stride variability on overall gait scores such as GPS and EVGS. Previous studies that compared gait kinematics and kinetics between children of different age groups, included averaged strides, ignoring the contribution of variability within these children [12,13,22,23]. They concluded that gait is mainly characterized by walking speed and not by age. Our results confirm that walking speed has effects on gait kinematics and especially kinetics in these children. However, the effect of age on kinematic variability and on the percentage of abnormal kinematic curves was also significant for most outcome parameters, even after correction for walking speed. These findings are further supported by the significant relation between age and GPS as well as a trend for EVGS. Thus, although walking speed plays an important role in kinematic outcomes, our study confirms that gait continues to mature during childhood when looking at its variability, and it might be important to consider benefits of age-specific reference data in terms of variation [10,24].

The laboratory environment may also impact the variability of the data. In line with our hypothesis, less stride-to-stride variability was found for treadmill walking compared to overground. It is debatable whether treadmill or overground walking gives a better representation of daily life gait in the outdoor world. However, treadmill walking may offer some benefits compared to overground walking, since it is easier to include more strides in order to provide a good estimate of a patient's gait. As an additional analysis, we explored the effect of incrementally averaging over 20 randomly selected strides for a subgroup of children walking in the treadmill (n = 23). As visualized in Fig. 4, averaging over a larger number of strides resulted in a reduced GPS score (more 'normal' gait). This effect seems to be more pronounced when looking at the RMS-scores for moments and powers, as shown by the rapid decline of RMS when averaged over several strides. This finding is in line with the greater number of abnormal strides found in kinetics. Unfortunately, the number of cycles in the present study varied between conditions and children, which restricted us to perform this latter analysis for the complete group. For overall interpretation, it is good to keep in mind that this varying number of strides was not random and overall more strides were collected for older children with a less variable gait pattern and for the treadmill condition, which may have affected our results. Hence, we would like to encourage future studies to investigate consequences including a larger number of overground strides in younger children.

Our findings have several implications for clinical gait analysis in paediatric patient populations, such as CP. Although further research is necessary to establish the stride-to-stride variability in CP, comparing a limited number of strides to a group averaged normative dataset, may lead to an incorrect estimation of gait deviations.

Several different approaches may be considered to reduce the impact of

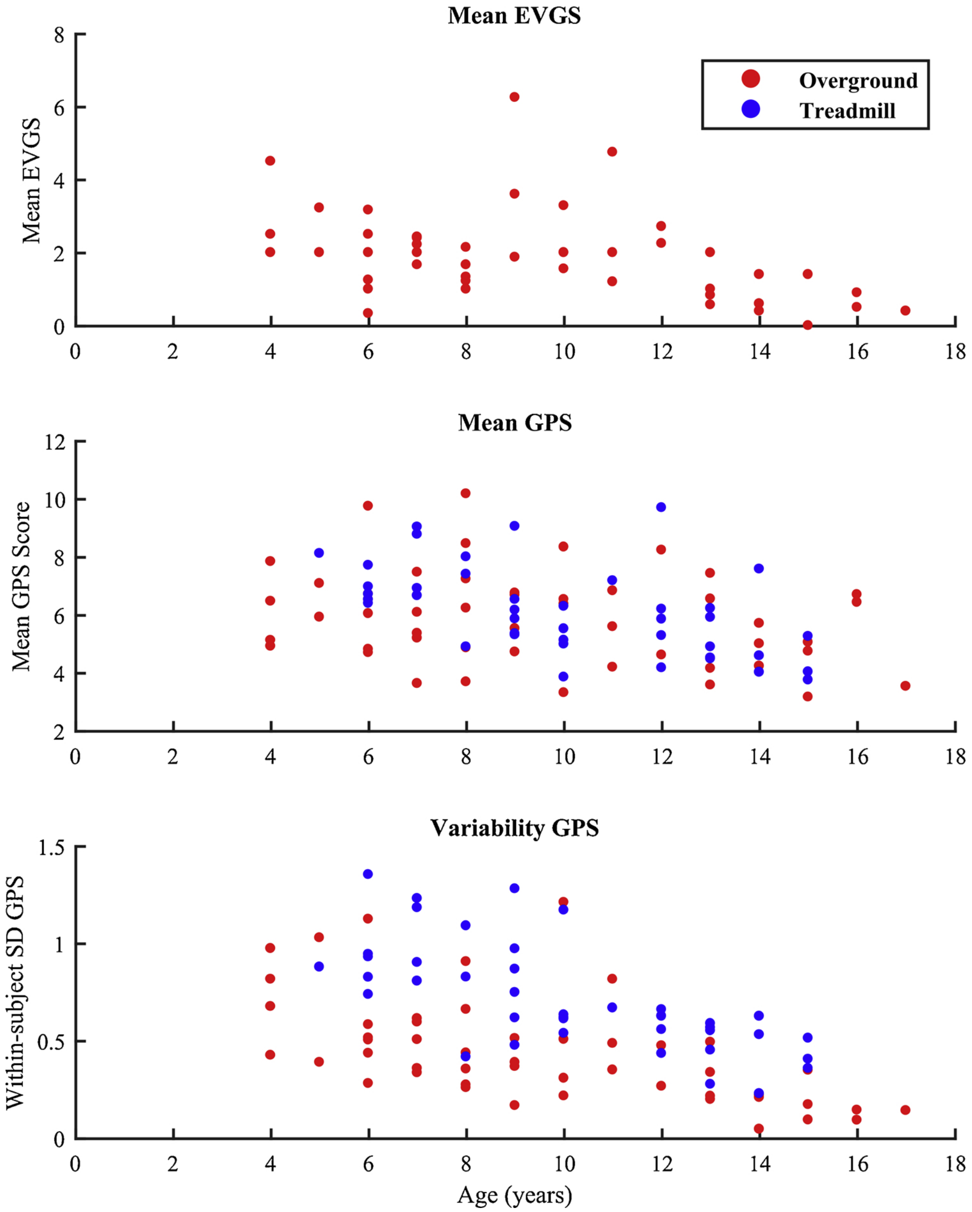

Fig. 3. Progression with age of the Edinburg Visual Gait Score (EVGS) (upper panel), gait profile score (GPS) (middle panel) and individuals standard deviation (lower panel), for the overground group (OG, red) as well as the treadmill group (TM, blue). Higher scores on GPS / EVGS indicate a more 'abnormal' gait pattern, based on deviations of the group average. Note that EVGS was only calculated for children walking in the overground gait laboratory, based on video analysis.

Fig. 4. Effect of incrementally averaging over 20 randomly selected strides for a subgroup of children walking in the treadmill (n = 23). Results are visualized for effects on root mean square errors (RMSE) as a sum score for joint kinematics (left), moments (middle) and kinetics (right).

the issues addressed in this study. Preferably, if a sufficient number of strides in a patient are available for analysis, averaging over a larger number of strides makes it more realistic to compare patient curves to a group average. In high-functioning children with CP, use of an instrumented treadmill provides a solution for this, since it allows for convenient collection of a large number of strides. However, in more severely affected children, walking on a treadmill might not be feasible and clinical gait analysis is restricted to a few strides in an overground gait lab. Therefore, as an alternative, if a limited number of strides are available, or if clinicians are specifically interested in peak values and variability between strides, it could be favourable to compare peak values to the actual peak values of the group. This could be implemented for example using a visual representation of peaks as in Fig. 2. Such a visualization can be helpful in patients with a variable gait pattern or for kinetic outcomes such as peak ankle push-off power.

Biomechanical gait analysis does not stand alone in guiding treatment decisions. Interpretation of clinical gait analysis is carried out in the light of underlying impairments assessed, using additional measures such as a standard physical examination and combining several gait features in a broader perspective. Therefore, although many normal strides were considered to be ‘abnormal’ in the present study, in clinical practice, deviations in individual gait curves may have limited influence on treatment decisions if other measures do not support the abnormality. Furthermore, the threshold of classifying strides as abnormal if 10% exceeded 2 SD may be considered arbitrary, however, this was chosen to reflect a considerable deviation from the grouped average.

In conclusion, when comparing individual strides to a grouped average curve, many strides may be incorrectly considered as abnormal. This is due to the stride-to-stride variability that is washed out when averaging to obtain reference curves. Effects are related to age, with younger children presenting a more variable gait pattern and as such a greater percentage of abnormal strides, regardless of walking on a treadmill or overground. These findings should be taken into account in the clinical interpretation of gait analysis data, especially in younger children.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.03.011.

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