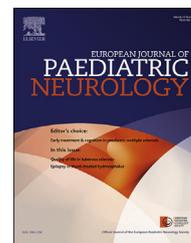




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## Original article

# Gait abnormalities in people with Dravet syndrome: A cross-sectional multi-center study



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## ABSTRACT

**Objective:** To quantify gait abnormalities in people with Dravet syndrome (DS).

**Methods:** Individuals with a confirmed diagnosis of DS were enrolled, and stratified according to knee flexion at initial contact (IC) and range of motion (ROM) during stance (atypical crouch: knee flexion >20° at IC and knee ROM >15° during stance; straight: knee flexion <20° at IC). A 1D ANOVA ( $\alpha = 0.05$ ) was used to test statistical differences among the joint kinematics and spatio-temporal parameters of the cohort and an age-matched control group. Clinical (neurological and orthopaedic evaluation) and anamnestic data (seizure type, drugs, genetic mutation) were collected; distribution between the two gait phenotypes was assessed with the Fisher exact test and, for mutation, with the chi-squared test ( $p < 0.05$ ). Linear regression between maximum knee flexion and normalised walking speed was calculated.

**Results:** Seventy-one subjects were enrolled and evaluated with instrumented gait analysis. Fifty-two were included in final analysis (mean age  $13.8 \pm 7.3$ ; M 26). Two gait patterns were detected: an atypical crouch gait (34.6%) with increased ankle, knee and hip flexion during stance, and reduced walking speed and stride length not associated with muscle-tendon retractions; and a pattern resembling those of healthy age-matched controls, but still

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showing reduced walking speed and stride length. No differences in clinical or anamnestic data emerged between the two groups.

*Significance:* Objectively quantified gait in DS shows two gait patterns with no clear-cut relation to clinical data. Kinematics abnormalities may be related to stabilization issues. These findings may guide rehabilitative and preventive measures.

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## 1. Introduction

Dravet syndrome (DS) is characterized by drug-resistant seizures, intellectual disability and neurological signs.<sup>1</sup> A mutation in the  $\alpha$ -subunit of the SCN1A sodium channel gene, is deemed causative in more than 80% of cases. At onset neurological examination is usually normal, but ataxic gait<sup>2</sup> may appear from early childhood. Extrapyramidal signs manifest with older age.<sup>3</sup> A report based on gait observational analysis described gait as “crouch”, with increased lower limb joint flexion and segments misalignment,<sup>4</sup> with onset in early teens. A putative link between gait impairment and genetic mutation has been suggested with mutations in the pore-forming region (PFR) of the SCN1A gene more likely to be associated with crouch gait.<sup>5</sup> Recently, electromyographic data suggested the coexistence of an axonal motor neuropathy,<sup>6</sup> considered a causative factor of crouch gait. Clinical experience, however, suggests that gait problems may appear much earlier, accounted by different abnormalities, and may change pattern from adolescents to adults. Full quantitative characterization of gait in people with DS could provide an alternative explanation for these features and clarify its natural history, allowing the design of rehabilitative/preventive measures.

Previous observations were based on observational gait analysis – i.e. standardized visual description of gait – due to the challenge of subjects’ collaboration for a full instrumental examination. Instrumental gait analysis provides quantitative information on human locomotion, but is more demanding in terms of equipment (Motion Analysis Laboratory), personnel expertise, and participant cooperation.

Our aim was to assess quantitatively gait in people with Dravet syndrome to identify biomechanical determinants of gait abnormalities.

## 2. Material and methods

Inclusion criterion was a genetically confirmed diagnosis. Subjects unable to walk without assistance or whose carers reported at least a convulsive seizure in the week prior to the examination were excluded.

Data were collected at the M<sup>2</sup>OCEAN Movement Analysis Laboratory, University of Antwerp, Belgium, and at the Laboratory of Clinical Analysis and Biomechanics of Movement, University Hospital of Padova, Italy. Subjects were recruited at: Pediatric Neurology Unit of Antwerp University Hospital

(Belgium); Istituto Neurologico C. Besta, Milano; University Hospital of Padova and Verona University Hospital (in Italy). Enrolment started in 2017 in Padova and in 2016 in Antwerp.

### 2.1. Standard protocol approvals, registrations, and patient consents

Legal guardians provided written informed assent. The study was approved by the Ethic Committees of Antwerp University Hospital (B300 2016 27079) and Padova (protocol number 4276/AO/17).

### 2.2. Anamnestic and clinical data

Anamnestic data collection included: pharmacotherapy, type/types of seizures, SCN1A gene mutation, severity of cognitive/behavioral impairment. Clinical data included: tests for ileopsoas, hamstrings and calf muscles contractures, Adam’s test to test for scoliosis, Root test for flat-foot identification.<sup>7</sup>

### 2.3. Gait analysis procedure

The subjects were equipped with the marker-set used in clinical practise (Davis protocol)<sup>12</sup> in Padova and with its modified commercial version (Plug-in-Gait with KAD – Knee Alignment Device) in Antwerp. Marker 3D trajectories were registered via the stereophotogrammetric systems (Padova: 10 cameras, SMART D-500, BTS Motion Capture, Italy - 200 Hz; Antwerp: 8 cameras, Vicon T10, Vicon Motion Systems, UK - 100 Hz). Subjects were asked to stand as still as possible and stare at a fixed point at their eye-level for a few seconds to acquire static data and then to walk barefoot at a self-selected speed back and forth within the capture volume. A minimum of five left and five right full strides per subjects were collected.<sup>9</sup> Video recordings were also collected during participants walking for preliminary observational analysis by using 3 video-cameras in Padova and 2 in Antwerp and scored according to the Rancho Los Amigos Observational Gait Analysis.<sup>13</sup>

Segmental (pelvic and foot) and joint (hip, knee and ankle) kinematics and spatiotemporal parameters calculation were run within the proprietary software (Vicon Nexus v1.8.6–2.1 in Antwerp, BTS SMART Tracker and Analyzer v1.5 in Padova), and according to the relevant biomechanical models. Kinematics were time-normalized over the percentage of the gait cycle (GC). Participants’ data were compared to age-matched healthy subject data assumed as control group, which were collected following the same procedure.

### Box 1 Basics of gait analysis.

Instrumental gait analysis provides quantitative information on human motion during walking: it measures ankle, knee and hip angles modifications during each step, quantifies forces between feet and floor, and measures spatiotemporal parameters, such as speed of walking and gait cycle timing. Reflective markers are placed on subjects by a trained operator according to a specified biomechanical model.<sup>8</sup> Subjects walk back and forth on a walkway with implanted force platforms until a certain number of full strides (3–6) is collected.<sup>9</sup> A system of infrared cameras, placed along the laboratory perimeter and conveniently calibrated, captures the 3D position of the markers during walking, while the force platforms register the foot contact forces with the floor.<sup>10,11</sup> Post-processing procedures provide the variables of interest (i.e., joint kinematics and dynamics, and spatio-temporal parameters), which are normalized over the percentage time of the gait cycle, body weight and height.<sup>9</sup> In particular, kinematics and dynamics are calculated on the sagittal, coronal and transversal planes of each articular joint, providing information on both angular joint modifications during each step and the interaction forces between the adjacent body segments. Spatio-temporal parameters, instead, describe the body movement as a whole: e.g. the walking speed, the number of complete strides the subject performs in a minute (cadence), the distance between feet while walking (stride width), or between two footsteps (stride length) [see Table A.1 in Supplemental materials for more details]. The obtained variables describe the implemented gait strategies, providing a more comprehensive picture of walking patterns and generated energies than what could be obtained by visual inspection alone (i.e., observational gait analysis).

Within-Subject consistency for each kinematic variable and each subject (people with DS and controls) was tested via visual inspection of the curves and subsequently via the robust score (R-score) method.<sup>14</sup> This method detects and excludes outliers when the R-score exceeds a predefined cut-off value. Typical cut-offs range between 2 (2.5% of type I error) and 3.5 (<1% of type I error).<sup>15</sup> For our dataset, the R-score was chosen equal to 3, as participants' gait was often observed to be poorly repeatable and lower cut-off would potentially lead to the exclusion of representative gait patterns. The selected strides were averaged for each participant, obtaining one curve per variable for the left and one curve for the right lower limb. For the controls, curves for right and left limbs were pooled, checked for outliers with the R-score<sup>14</sup> and averaged, obtaining one representative curve per variable. Data analyses and results were run and discussed separately for the two centres, as pooling the data would imply comparing outcomes obtained with two different biomechanical protocols and models, with relevant variables defined and calculated with different and, thus not directly comparable, approaches.<sup>16,17</sup>

### 2.4. Data analysis

Observational Gait Analysis (Rancho Los Amigos Observational Gait Analysis) findings suggested the presence of various degrees of knee flexion throughout the gait cycle in DS.<sup>13</sup> Given the lack of a consensus on knee angle flexion cut-offs to define crouch gait,<sup>18</sup> we adopted the following cut-offs of knee flexion to stratify people with DS: atypical-crouch (AC, see results section for data supporting the definition of atypical) with knee flexion  $>20^\circ$  at initial contact (IC) and knee range of motion (ROM)  $>15^\circ$  over the stance phase (St),<sup>19</sup> and straight (S) walkers, with knee flexion  $<20^\circ$  at IC.<sup>20</sup>

#### 2.4.1. Anamnestic and clinical data

Differences in the distribution of anamnestic and clinical data between the two gait phenotypes (i.e., AC and S) were assessed with the chi-squared test ( $p$ -value  $<0.05$ ).

#### 2.4.2. Gait analysis variables

A 1D ANOVA ( $\alpha = 0.05$ ) was used to test statistical differences among the kinematics of the participants' sub-groups and controls (C).<sup>21</sup> The 1D ANOVA is based on the Statistical Parametric Mapping (SPM) theory,<sup>22</sup> which is used to analyse statistical differences among continuous variables, without reducing the test to summary metrics (such as maximum or minimum values at specific instants of the gait cycle) that potentially lead to false positives or negatives.<sup>23</sup> This methodology allows considering the time-continuous variables (such as human joint kinematics) as composed by points that are not independent from each other: they represent the evolving values of the same variable. The analysis was performed using the SPM1D open-source package for MATLAB ([spm1d.org](http://spm1d.org)) and generated: map of  $F$ -values (SPM{F}),  $F^*$  limit and areas where differences were found with relevant  $p$ -values. In case statistical differences emerged, a Bonferroni correction was considered for the post-hoc test. A classical one-way ANOVA ( $\alpha = 0.05$ ) was performed on spatiotemporal parameters among DS groups and controls, followed by a Bonferroni correction for post-hoc tests when relevant.

In order to better understand the walking strategies, a linear regression between the maximum knee flexion angle and the normalised walking speed was calculated ( $a_1$  and  $a_0$  are the regression coefficients, with  $a_1$  indicating the line slope;  $R^2$  is a measure of the data dispersion; the  $p$ -value provides the significance of the linear model – i.e.  $p < 0.05$  was considered as significant).

## 3. Results

Seventy-one participants were enrolled, 31 in Antwerp and 40 in Padova. One subject in Antwerp was excluded due to an additional diagnosis of cerebral palsy. Eighteen subjects in Padova failed to cooperate with the procedure and stereophotogrammetric data were not obtained (see Fig. 1 for study flow-chart). Three of these subjects were obese and markers could not be positioned appropriately; eleven did not collaborate and marker positioning, walking on the walkway for a sufficient number of strides, or maintaining a still posture for

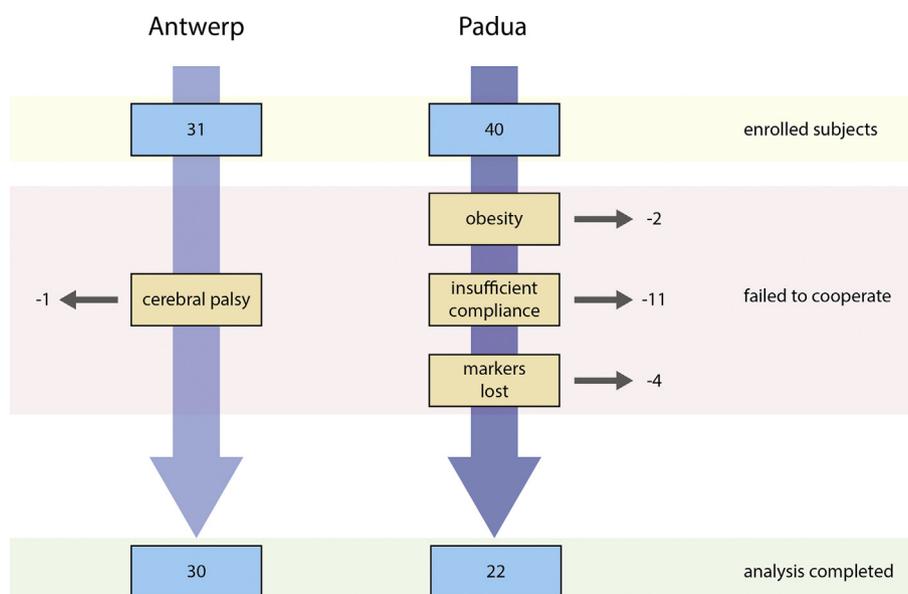


Fig. 1 – Flow chart of the study.

at least 15 s for static data acquisition was not possible; in 4 cases technical issues arose (e.g. repositioning of markers). Of note, 12 of these subjects presented a diagnosis of severe cognitive impairment and/or behavioural problems. Only in the Italian cohort, 2 subjects were not referred to the lab due to lack of independent gait (one 26 years old male, whose gait deteriorated over time, and a 9 years-old obese girl with severe cognitive impairment). The occurrence of seizures in the previous week did not impact on the number of enrolled subjects: families were aware of this constraint and the visit to the lab was re-scheduled.

### 3.1. Observational gait analysis

Observational Gait Analysis identified two knee flexion patterns (normal, excessive flexion), which provided the preliminary subdivision based on gait angle degrees during stance, confirmed by instrumental gait analysis.

### 3.2. Anamnestic and clinical data

Clinical and demographic data are reported in Table 1 & Fig. 2. No statistical differences emerged among the three groups (AC, S and controls) for age, body mass, height, BMI and leg length. Clinical presence of scoliosis, flatfoot or valgus knee, type of antiepileptic drug, seizure types and kind of SCN1A

mutation (classified as missense, truncating, nonsense, splice site, and frameshift) did not show any difference between the two gait phenotypes. The prevalence of scoliosis in our DS cohort was 13,7% and flat foot 54,9% on the right and 58,8% on the left. Only one subject had shortening of hamstrings muscles.

The 19.7% of the included subjects presented with mild intellectual disability (10 subjects in Padova, 4 in Antwerp), 33.8% with a moderate intellectual disability (11 subjects in Padova, 13 in Antwerp) and 21.1% with a severe intellectual disability (9 subjects in Padova, 6 in Antwerp). The 15.5% presented with behavioural problems (6 subjects in Padova, 5 in Antwerp). Data from 18 subjects (11 subjects in Padova, 7 in Antwerp) were missing.

### 3.3. Gait analysis variables

Since different biomechanical models were used at the two centres, kinematic variables are not directly comparable and were analysed separately.

#### 3.3.1. Spatiotemporal parameters

Spatiotemporal parameters (raw values and statistical significance) are reported in Table 2. In both laboratories, DS subjects walked at lower speed (Antwerp lab: AC < C:  $p = 0.003$ ; Padova lab: AC < C:  $p = 0.002$ ; S < C:  $p < 0.001$ ) and had a

Table 1 – Demographics of the two cohort of people with Dravet (AC and S) and the Control group (C) in Antwerp and Padova.

Parameter	Units	ANTWERP				PADOVA			
		AC (9)	S (21)	C (10)	ANOVA	AC (9)	S (13)	C (10)	ANOVA
Age	years	14.3 ± 7.3	8.7 ± 4.4	9.2 ± 3.9	ns	15.1 ± 7.1	17.6 ± 8.0	21.4 ± 7.7	ns
Body mass	kg	48.0 ± 21.6	36.1 ± 20.0	31.0 ± 15.2	ns	38.7 ± 9.6	49.1 ± 20.2	57.1 ± 25.0	ns
Height (H)	m	1.48 ± 0.30	1.38 ± 0.30	1.36 ± 0.26	ns	1.45 ± 0.14	1.53 ± 0.22	1.60 ± 0.29	ns
BMI	kg/m <sup>2</sup>	20.40 ± 4.79	17.24 ± 3.87	15.91 ± 2.39	ns	18.17 ± 2.94	20.01 ± 4.35	20.61 ± 4.96	ns
Leg Length (LL)	m	0.80 ± 0.18	0.82 ± 0.40	0.71 ± 0.15	ns	0.76 ± 0.09	0.82 ± 0.13	0.83 ± 0.19	ns

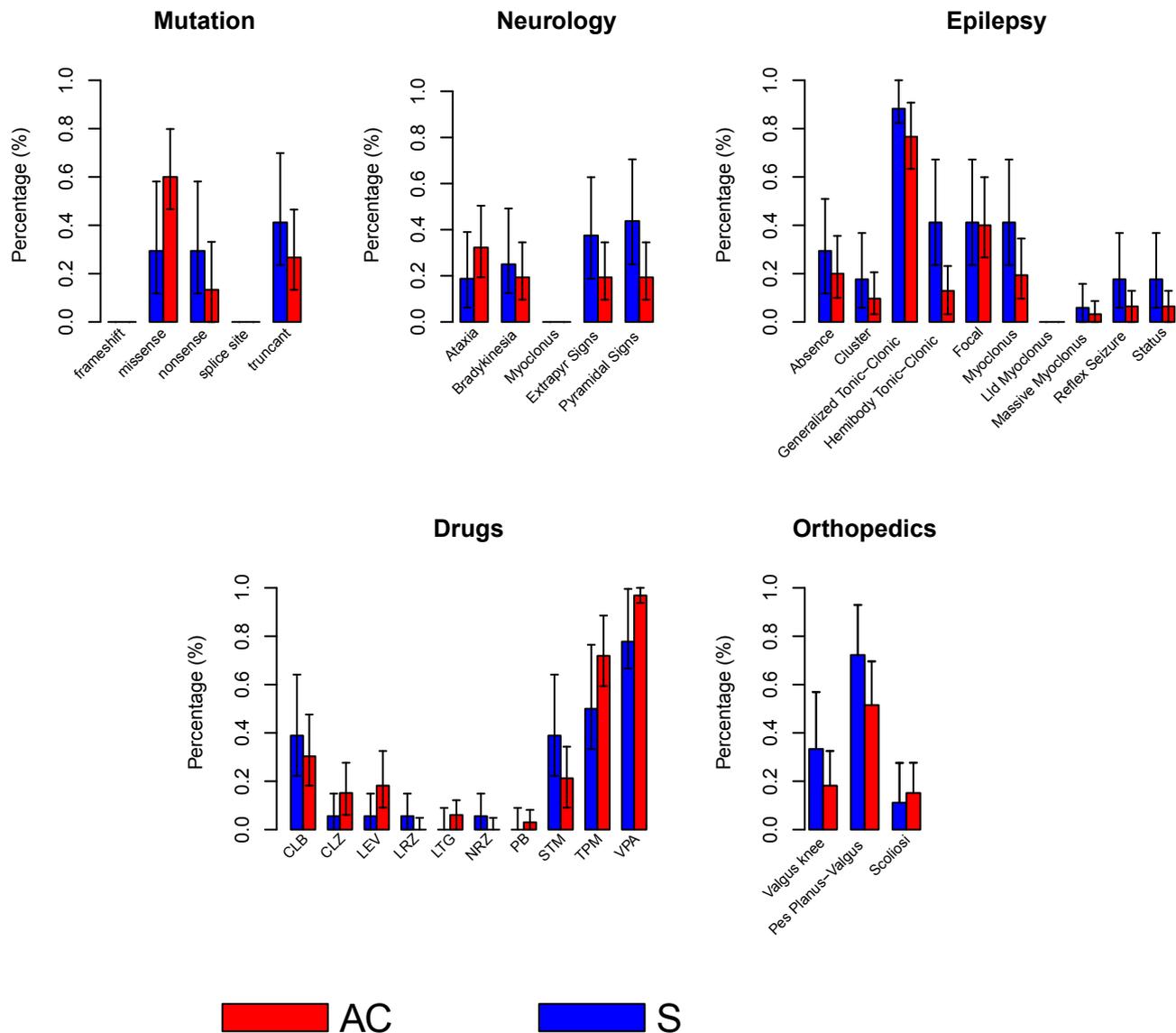


Fig. 2 – Clinical and Anamnesic data.

reduced stride length than controls (Antwerp: AC < C:  $p = 0.001$  on the right and  $0.002$  on the left; S < C:  $p = 0.01$  on the right; Padova: AC < C:  $p < 0.001$  on the right and  $0.004$  on the left; S < C:  $p = 0.002$  on the right and  $0.002$  on the left). Step width was significantly increased in DS (Antwerp: AC > C:  $p < 0.001$ ; S > C:  $p = 0.003$ ).

### 3.3.2. Joint kinematics

In the Padova cohort (see Figs. 3 and 4), kinematic data showed a persistent pelvic anteversion in AC (AC > S:  $p < 0.01$ ) during the whole gait cycle, associated with increased hip flexion over the gait cycle (AC > C:  $p < 0.01$ ; AC > S:  $p < 0.01$ ) and increased knee flexion during stance (AC > C:  $p < 0.01$ ; AC > S:  $p < 0.01$ ) and mid-terminal swing (80–100% of the gait cycle; AC > C:  $p < 0.01$ ; AC > S:  $p < 0.01$ ) bilaterally. On the left side an increased ankle dorsiflexion during loading response (5–30% of gait cycle) was detected (AC > C:  $p < 0.01$ ; AC > S:  $p < 0.01$ ). No significant differences emerged for the straight walkers'

group in comparison with controls, despite the increased kinematic curves' variability.

In the Antwerp cohort (Figures A.1 and A.2), kinematic data from the atypical-crouch gait did not differ from those collected in the Padova lab. Straight walkers in Antwerp showed an increased hip flexion in terminal stance (35–60% of gait cycle; S > C:  $p < 0.01$ ) and increased plantar flexion in loading response (8–20% of gait cycle; S > C:  $p < 0.01$ ).

### 3.3.3. Walking speed and knee flexion correlation

For the Padova cohort, two outliers were removed before the analysis of the Straight group. These two participants with DS, although being correctly classified as Straight walkers, showed an akin stiff-knee walking pattern, with a strong hip strategy to grant a good clearance during the gait cycle. Two additional outlier values were not included in the analysis: one for the right side in the S group and one for the left side in the AC group.

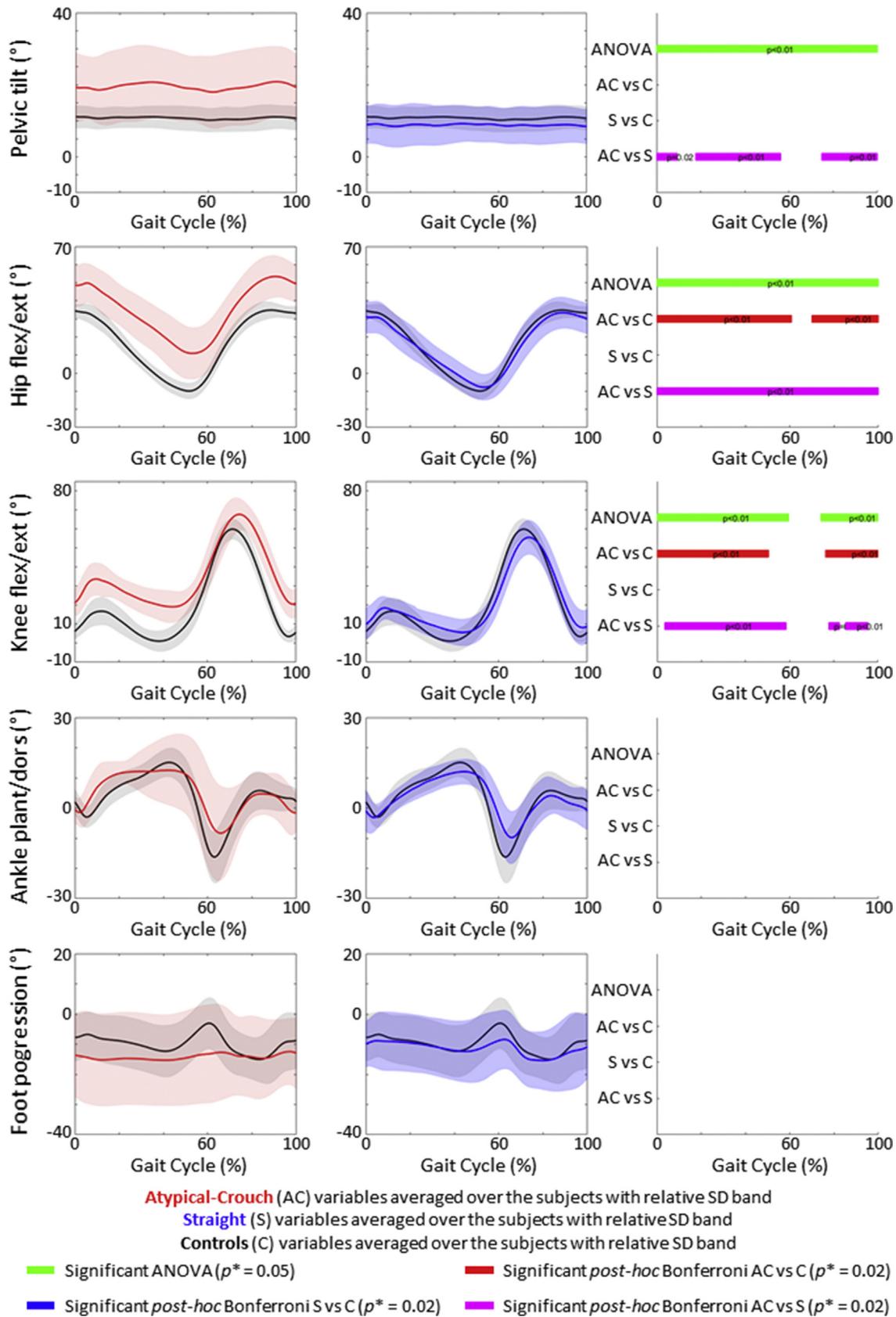
**Table 2 – Spatio-temporal parameters and statistical significance between atypical crouch (AC) versus controls (C), atypical crouch (AC) versus straight walkers (S), and straight walkers (S) vs controls (C).**

	Parameter	Units	AC	S	C	ANOVA	AC vs C	S vs C	AC vs S
ANTWERP	Right StanceTime	s	0.56 ± 0.23	0.59 ± 0.14	0.52 ± 0.09	ns			
		%GC	62.52 ± 2.48	60.87 ± 3.49	58.96 ± 2.57	ns			
	Left StanceTime	s	0.55 ± 0.23	0.57 ± 0.12	0.52 ± 0.09	ns			
		%GC	61.75 ± 2.63	60.54 ± 3.22	58.96 ± 2.57	ns			
	Right SwingTime	s	0.34 ± 0.13	0.37 ± 0.06	0.36 ± 0.06	ns			
		%GC	37.48 ± 2.48	39.13 ± 3.49	41.05 ± 2.57	ns			
	Left SwingTime	s	0.34 ± 0.13	0.37 ± 0.07	0.36 ± 0.06	ns			
		%GC	38.25 ± 2.63	39.46 ± 3.22	41.05 ± 2.57	ns			
	Right Single Support	s	0.39 ± 0.05	0.38 ± 0.07	0.38 ± 0.05	ns			
		%GC	38.86 ± 1.53	39.80 ± 2.51	40.88 ± 1.93	ns			
	Left Single Support	s	0.39 ± 0.05	0.37 ± 0.06	0.38 ± 0.05	ns			
		%GC	38.69 ± 2.48	39.48 ± 3.20	40.88 ± 1.93	ns			
	Right Double Support	s	0.24 ± 0.08	0.20 ± 0.08	0.17 ± 0.05	ns			
		%GC	23.25 ± 6.24	20.24 ± 5.47	18.30 ± 3.63	ns			
	Left Double Support	s	0.24 ± 0.06	0.20 ± 0.08	0.17 ± 0.05	ns			
		%GC	23.48 ± 4.23	21.12 ± 6.36	18.30 ± 3.63	0.04	0.003	ns	ns
	Right StrideLength	m	0.97 ± 0.24	0.97 ± 0.29	1.16 ± 0.21	ns			
		%H	1.16 ± 0.33	1.29 ± 0.38	1.63 ± 0.18	0.01	0.001	0.01	ns
Left StrideLength	m	0.98 ± 0.24	0.98 ± 0.26	1.16 ± 0.21	ns				
	%H	1.25 ± 0.27	1.37 ± 0.30	1.63 ± 0.18	0.01	0.002	0.016	ns	
Right StrideTime	s	1.00 ± 0.12	0.96 ± 0.19	0.93 ± 0.15	ns				
	s	1.00 ± 0.14	0.94 ± 0.18	0.93 ± 0.15	ns				
Walking Speed	m/s	0.97 ± 0.17	1.03 ± 0.29	1.26 ± 0.19	0.03	0.003	ns	ns	
	%H/s	0.68 ± 0.17	0.81 ± 0.27	0.94 ± 0.21	0.03	0.009	ns	ns	
Step Width	m	0.19 ± 0.05	0.20 ± 0.09	0.11 ± 0.02	0.005	<0.001	0.003	ns	
PADOVA	Right StanceTime	s	0.66 ± 0.17	0.72 ± 0.10	0.63 ± 0.07	ns			
		%GC	61.16 ± 4.03	61.60 ± 3.00	59.57 ± 1.63	ns			
	Left StanceTime	s	0.69 ± 0.20	0.73 ± 0.09	0.63 ± 0.07	ns			
		%GC	62.61 ± 4.63	61.90 ± 2.26	59.57 ± 1.63	ns			
	Right SwingTime	s	0.41 ± 0.04	0.44 ± 0.06	0.43 ± 0.04	ns			
		%GC	38.83 ± 4.06	38.27 ± 3.03	40.46 ± 1.63	ns			
	Left SwingTime	s	0.40 ± 0.04	0.45 ± 0.06	0.43 ± 0.04	ns			
		%GC	37.32 ± 4.65	38.88 ± 2.08	40.46 ± 1.63	ns			
	Right Single Support	s	0.39 ± 0.03	0.45 ± 0.05	0.43 ± 0.04	0.03	ns	ns	0.012
		%GC	37.56 ± 4.44	38.85 ± 2.20	40.61 ± 1.34	ns			
	Left Single Support	s	0.41 ± 0.05	0.45 ± 0.06	0.43 ± 0.03	ns			
		%GC	38.40 ± 3.48	38.66 ± 3.66	40.42 ± 2.00	ns			
	Right Double Support	s	0.13 ± 0.06	0.14 ± 0.03	0.10 ± 0.02	ns			
		%GC	11.97 ± 3.07	12.05 ± 2.91	9.49 ± 1.54	ns			
	Left Double Support	s	0.13 ± 0.06	0.13 ± 0.04	0.10 ± 0.02	ns			
		%GC	11.56 ± 3.54	11.13 ± 2.68	9.48 ± 1.41	ns			
	Right StrideLength	m	0.98 ± 0.18	1.05 ± 0.21	1.33 ± 0.19	0.001	<0.001	0.004	ns
		%H	68.00 ± 12.36	68.43 ± 8.67	79.73 ± 5.93	0.01	0.016	0.002	ns
Left StrideLength	m	0.99 ± 0.17	1.05 ± 0.21	1.33 ± 0.19	0.001	<0.001	0.003	ns	
	%H	68.53 ± 11.96	68.16 ± 8.71	79.73 ± 5.93	0.01	ns	0.002	ns	
Right StrideTime	s	1.07 ± 0.20	1.17 ± 0.13	1.06 ± 0.11	ns				
	s	1.08 ± 0.22	1.17 ± 0.15	1.06 ± 0.11	ns				
Walking Speed	m/s	0.91 ± 0.24	0.91 ± 0.21	1.24 ± 0.13	<0.001	0.002	<0.001	ns	
	%H/s	67.1 ± 10.9	61.9 ± 11.7	75.8 ± 11.7	0.026	ns	0.01	ns	
Step Width	m	0.12 ± 0.17	0.12 ± 0.05	0.06 ± 0.03	0.02	ns	0.006	ns	

Overall, normalised walking speed and maximum knee flexion provided significant correlation at both centres, with knee flexion increasing as walking speed increases (maximum *p*-value 0.02, see [Figure A.3](#) and [A.4](#) in the Supplemental Materials). The only exception was obtained for the AC group enrolled at the University of Antwerp (*p*-values 0.36 and 0.39 for the left and right side, respectively), with the cloud of points showing no clear trend and yielding a low *R*<sup>2</sup> value (0.12 and 0.11 for the left and right side, respectively).

#### 4. Discussion

Our results confirm abnormalities of gait in DS, objectively quantified, and provide evidence of two distinct patterns. The first pattern, which we defined “atypical-crouch” (AC), displays marked knee and hip flexion throughout stance associated with increased ankle dorsiflexion in loading response and increased step width. The second, defined as “straight”



**Fig. 3** – Kinematics obtained on the sagittal plane for the right side for controls (bands in black), atypical-crouch (red) and straight (blue). Data recorded in the University of Padova Movement Analysis laboratory. Bands are centred on the average curve and encompass 1 standard deviation. Differences from the 1D statistical analysis are highlighted in: green) for the ANOVA, red) for the *post-hoc* AC vs C, blue) S vs C, and magenta) for the *post-hoc* AC vs S. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

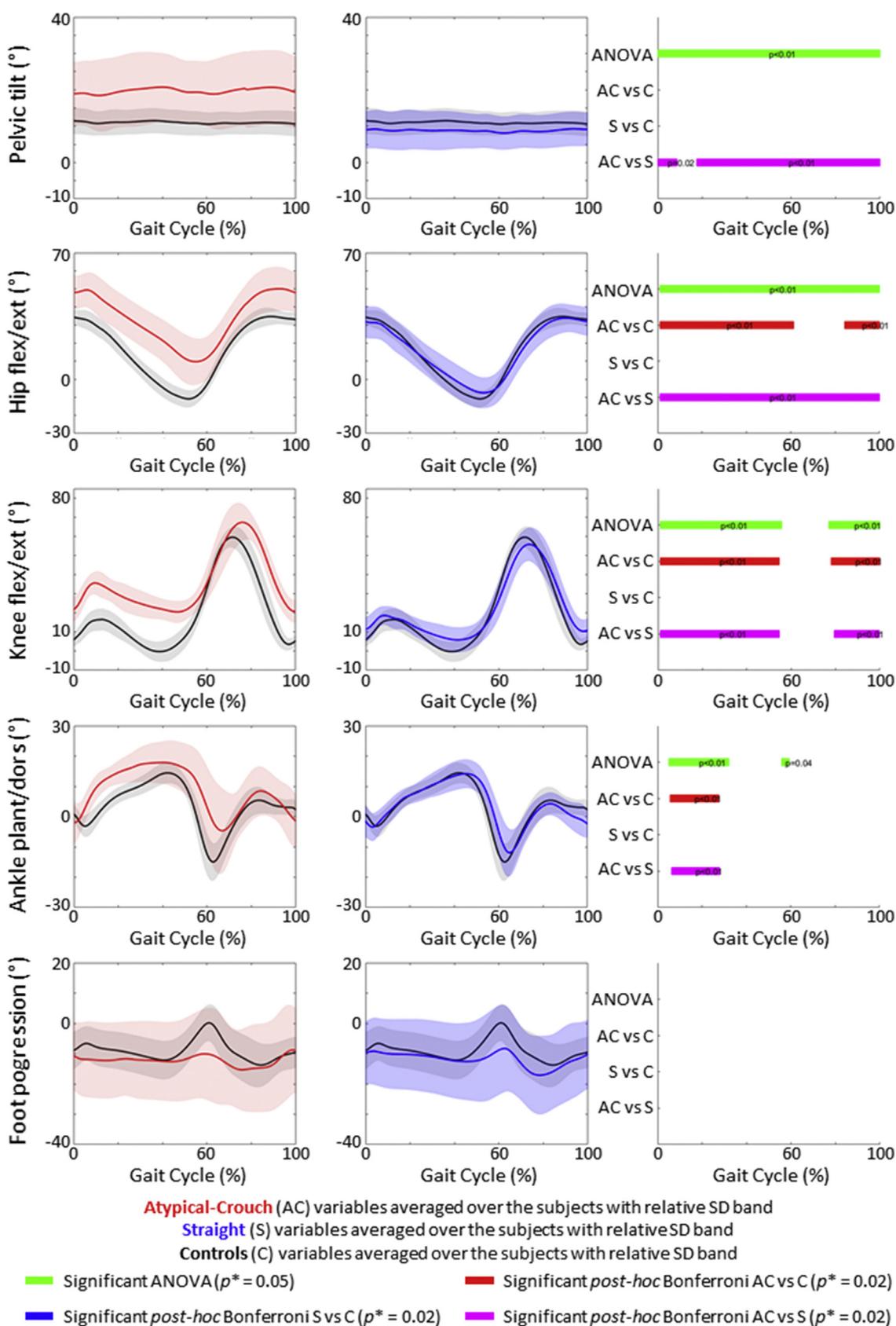


Fig. 4 – Kinematics obtained on the sagittal plane for the left side for controls (bands in black), atypical-crouch (red) and straight (blue). Data recorded in the University of Padova Movement Analysis laboratory. Bands are centred on the average curve and encompass 1 standard deviation. Differences from the 1D statistical analysis are highlighted in: green) for the ANOVA, red) for the *post-hoc* AC vs C, blue) S vs C, and magenta) for the *post-hoc* AC vs S. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(S), does not substantially differ from those of healthy age-matched volunteers, except for an increased hip flexion in terminal stance and increased step width.

Previous reports have described DS walking as “crouch-gait”, with almost all developing this by the age of 13 years.<sup>4,5</sup> Crouch gait definition includes increased ankle, knee and hip flexion during the whole gait cycle, plus rotations of the femur and/or tibia and muscle retractions. This pattern is well described in children with cerebral palsy (CP): in this population, crouch gait is typically related to ankle plantar-flexors weakness, lever arm dysfunctions due to skeletal deformities, knee and hip flexor, and hamstrings contractures.<sup>24</sup> We used the definition of “atypical crouch” in DS in light of the increased joint flexion prevalent during stance but less evident in swing and the lack of association with muscle contractures, as it is in the case of CP. Most likely atypical-crouch gait denotes a strategy to stabilize walking: the increased step width and the increased flexion of the three joints in the legs lowers the Centre of Mass (CoM), augmenting the area of the support base, and, thus, increasing stability. A stabilization mechanism could also be present in the second pattern (Straight) as a widening of the step width, which was indeed statistically significant only in the Antwerp cohort. The results highlighted an increased stance and double support time in DS compared to swing and single support (see Table 2). As an example, these averaged results expressed in percentage of the gait cycle time (%GC), obtained for the left side in Padova, were: stance time equal to 62.61 %GC (CI<sub>95%</sub>: 9.26) for AC, 61.90 %GC (CI<sub>95%</sub>: 4.52) for S and 59.57 %GC (CI<sub>95%</sub>: 3.26) for the control group; double support equal to 11.56 %GC (CI<sub>95%</sub>: 7.08) for AC, 11.13 %GC (CI<sub>95%</sub>: 5.36) for S and 9.48 %GC (CI<sub>95%</sub>: 2.82) for the control group; swing time equal to 37.32 %GC (CI<sub>95%</sub>: 9.30) for AC, 38.88 %GC (CI<sub>95%</sub>: 4.16) for S and 40.46 %GC (CI<sub>95%</sub>: 3.26) for the control group; single support time equal to 38.40 %GC (CI<sub>95%</sub>: 6.96) for AC, 38.66 %GC (CI<sub>95%</sub>: 7.32) for S and 40.42 %GC (CI<sub>95%</sub>: 4.00) for the control group. In fact, this finding lacks statistical significance: prolonged stance or double support could hint to a greater instability, which is effectively balanced by the adopted stabilization strategy.

The analysis of the correlation between walking speeds and knee flexion angles of people with DS reported good correlations in both centres (i.e., higher walking speed related to larger knee flexion during swing), which is in line with the biomechanics of walking. Unexpectedly, no correlation was obtained for the AC group enrolled at the University of Antwerp. By definition, the AC group should be characterised by a higher knee flexion during swing than S group, as for the Padova cohort. Instead, the AC group in Antwerp showed scattered results and maximum knee flexion angles (ranging between 50° and 75°) comparable with those of the S group (between 46° and 77°). Knee flexion angles over the whole gait cycle in Padova (Figs. 3 and 4) and in Antwerp (Figure A.1 and A.2) were compared: differences between AC and S were obtained both in stance and swing in Padova but only in the stance in Antwerp. This finding has no clear-cut interpretation and we can only speculate on it: differences in the adopted biomechanical models, and specifically in the knee angles calculation, could have affected the results. Indeed, according to the Davis protocol,<sup>12</sup> the

knee flexion axis was calculated starting from physical markers attached on the participant's skin in Padova, whereas the KAD (knee alignment device) was used in Antwerp. KAD virtually registers the knee flexion axis during standing and its reconstruction is subsequently performed starting from the physical and virtual markers of the lower limb. Therefore, different cross-talks between flexion-extension movement and non-sagittal rotations (i.e. internal-external rotation and ab-adduction) may have concealed higher expected knee flexions in the AC group during swing.<sup>25</sup> Further investigations are still needed to clarify this aspect. A longitudinal study with a larger sample is ongoing, with data collected each year for 5 consecutive years. This wealth of data may contribute to clarify this issue.

Gait abnormalities appear quite early in the natural history (as early as 4 years of age), in contrast with previous reports.<sup>4,4</sup> Only a minority (9/30 in Antwerp and 9/22 in Padova) developed AC, with no clear-cut age distribution. This is different from observational data,<sup>4</sup> which report that by the age of 13 years up to 80% of people with DS walk with a “crouch gait”. The determinants of gait pattern and how to develop individualized rehabilitative and preventive measures are still to be elucidated.

A previous report<sup>6</sup> postulated a motor neuropathy, as the causative factor of crouch gait. We cannot exclude a neuropathy contributing to plantarflexor muscles weakness, but in our view different factors, including biomechanical ones, such as flat foot, contribute to the gait disturbances. Identifying causative biomechanical factors opens up new perspectives in terms of rehabilitative approaches. Foot lever dysfunctions can be corrected with insoles to restore proper propulsion; ankle-foot orthosis with an anterior rigid tibial shell (e.g. GRAFO<sup>26</sup>) can reduce excessive tibial ante-position and consequently reduce knee flexion.

The lack of a clear-cut correlation with clinical findings was surprising: based on clinical observation alone, we hypothesised the presence of different clinical signs in the two groups or different drug regimens. Larger cohorts are likely needed to confirm this finding.

Even if there is no difference in term of orthopaedic abnormalities (scoliosis, pes planus, knee valgus) between the two groups, it is of note that the prevalence of scoliosis and pes planus in our DS population is higher than in the general population (scoliosis in DS 13,7% vs 7% in general population, flatfoot 55% ca vs 5%).<sup>27–30</sup> This may be determined by ligament hyperlaxity, a frequent clinical finding in DS: hyperlaxity may be caused by the antiepileptic polytherapy, but we cannot exclude an articular-capsule and ligaments involvement due to the pathology itself and which could be the focus of further research.

Our study has limitations. We did not factor in possible effects of duration of treatment, which has been reported to affect motor development. Seizure frequency was also not taken into account, although we excluded subjects who had a convulsive seizure in the previous week to avoid carry-over effects. Community functioning data were collected, but questionnaires/evaluations were heterogeneous between centres: the Padova Lab administered the Functional Independence Measure (FIM)<sup>31</sup> or the WeeFIM (Functional

Independence Measure in Children)<sup>32</sup> in children aged 8 or younger, whereas in Antwerp data focused on mobility, based on the Functional Mobility Scale (FMS).<sup>33</sup> In light of the heterogeneity of these data and the non-specificity of the scales, we considered more appropriate not to report these findings. The scarce consistency of trials, related to cognitive and behavioural deficits, was most likely responsible for the high standard deviations, which reduce statistical significance. Lastly, the cohort in Padova had a high number of non-collaborative subjects with severe behavioural disturbances, which had to be excluded from final analysis. While we have no clear hypothesis for this observation, we observe that the whole population referred to Padova (more than 50 subjects) may have included also more cognitively/behaviourally impaired individuals.

An intriguing question is what the different patterns we identified represent: are they part of the same spectrum or do they represent truly different patterns with a diverse natural history? Will we be able to modify their evolution through focused rehabilitative programs and/or orthosis? Longitudinal data can hopefully provide more insight into these issues.

### Data availability statement

We will share the data supporting these findings with researchers upon reasonable request to the corresponding author.

### Disclosures of conflicts of interest

RdM, AH, GB, FR, EP, TG, ASS, PVW, FD, BDB, MV, ZS, BS, SM, MGB report no disclosure.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ejpn.2019.09.010>.

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