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

Gait abnormalities in people with Dravet syndrome: a ~~longitudinal~~ cross-sectional multi-center study

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Keywords: SCN1A mutation, gait analysis, crouch gait, comorbidity.

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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. They were stratified according to knee flexion at initial contact (IC) and range of motion (ROM) during stance [crouch gait if knee flexion >20° at IC and knee range of motion (ROM) >15°; straight gait: 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 orthopedic 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-value < 0.05).

Results: Seventy-one subjects were enrolled and evaluated with instrumented gait analysis. Fifty-two were included in the final analysis (mean age 13.8 ± 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 without any muscle-tendon retraction; and a pattern resembling those of healthy age-matched controls, but still showing reduced walking speed and stride length. No difference 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. Kinematic parameters abnormalities are likely due to stabilization issues. These findings may guide rehabilitative and preventive measures.

Keywords: SCN1A mutation, gait analysis, crouch gait, comorbidity.

Highlights

- Dravet syndrome presents a clear-cut gait abnormality, “atypical crouch gait” (AC)
- AC does not present major orthopaedic deviation as typical crouch gait
- No correlation with genetic mutation, seizure types, and antiepileptic treatment

1 Introduction

Dravet syndrome (DS) is characterized by drug-resistant seizures, intellectual disability and neurological signs [1]. A mutation in the α-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 [2] may appear from early childhood. Extrapyramidal signs manifest with older age [3]. A report based on gait observational analysis described gait as "crouch", with increased lower limb joint flexion and segments misalignment [4], 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 [5]. Recently, electromyographic data suggested the coexistence of an axonal motor neuropathy [6], 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 gait analysis. 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 M²OCEAN 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 the Pediatric Neurology Units of Antwerp University Hospital (Belgium), Istituto Neurologico C. Besta, Milano, Padova University Hospital, and Verona University Hospital (both in Italy). Enrollment 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 [7].

2.3 Gait Analysis procedure

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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 [8]. Subjects walk back and forth on a walkway with implanted force platforms until a certain number of full strides (3-6) is collected [9]. 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 [10,11]. 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 [9]. 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 the walking patterns and the generated energies than what could be obtained by visual inspection alone (i.e., observational gait analysis).

BOX 1 Caption: Basics of Gait Analysis.

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The subjects were equipped with the marker-set used in clinical practice (Davis protocol) [12] 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 [9]. 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 [13].

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 (C: Padova: 10 subjects, mean age 21.4 ± 7.7 years; Antwerp: 10 subjects, 14.3 ± 7.3), which were collected following the same procedure.

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 [14]. 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) [15]. 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 [14] and averaged, obtaining one representative curve per variable. Data analyses and results will be performed and discussed separately for the two centers, as pooling the data would imply comparing ~~variables~~ outcomes obtained with two different biomechanical protocols and models, with the relevant variables defined differently and, thus, not directly comparable [16,17].

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 [13]. Given the lack of a consensus on knee angle flexion cut-offs to define crouch gait [18], 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° at initial contact (IC) and knee range of motion (ROM) >15° over the stance phase (St) [19], and straight (S) walkers, with knee flexion <20° at IC [20].

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) [21]. The 1D ANOVA is based on the Statistical Parametric Mapping (SPM) theory [22], which is used to analyze 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 [23]. 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) 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. Moreover, in order to better understand the walking strategies, the 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, and the *p*-values gives 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 Figure 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 at least 15 seconds 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 ~~2~~ 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 & Figure 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). 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

~~Data were analysed separately for each laboratory. Indeed,~~ Since different biomechanical models were used at the two centres,~~. The~~ kinematic variables ~~are defined differently and,~~

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

INSERT TABLE 2 HERE

3.3.2 Joint kinematics

In the Padova cohort (see Figures 3 and 4), kinematic data showed a persistent pelvic anteversion in AC (AC vs S: $p<0.01$) during the whole gait cycle, associated with increased hip flexion over the gait cycle (AC vs C: $p<0.01$; AC vs S: $p<0.01$) and increased knee flexion during stance (AC vs C: $p<0.01$; AC vs S: $p<0.01$) and mid-terminal swing (80-100% of the gait cycle; AC vs C: $p<0.01$; AC vs S: $p<0.01$) bilaterally. On the left side an increase ankle dorsiflexion during loading response (5-30% of gait cycle) was detected (AC vs C: $p<0.01$; AC vs 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 vs C: $p<0.01$) and increased

plantar flexion in loading response (8-20% of gait cycle; S vs C: $p<0.01$).

3.3.3 Walking speed and knee flexion correlation

For the Padua cohort, two outliers were removed before the analysis of the Straight group. These two people 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.

Overall, normalised walking speed and maximum knee flexion gave good and significant correlation at both centres, with knee flexion increasing as walking speed increases (maximum p-value equal to 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 equal to 0.36 and 0.39 for the left and right side, respectively), with the cloud of points showing no clear trend and giving a low R^2 (0.12 and 0.11 for the left and right side, respectively).

4 Discussion

We confirmed abnormalities of gait in DS, objectively quantified, and we identified two distinct patterns. It is worthy to underline that, although data from both centres confirm the same trend and no loss of significance for the discussion is implied, data cannot be pooled together as two different biomechanical models have been considered in the two centres and results had to be interpreted separately.

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” (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 age 13 years [4,5]. 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 [24]. 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 is the case in 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. Even though the ANOVA on the temporal parameters was not significant, data highlighted a trend towards increased stance time, as well as in double support time compared to swing and single support, respectively. Despite the neurological signs presented by our cohort, the lack of significantly prolonged stance or double support could be interpreted as a good efficacy of the motor strategy.

The analysis on the correlation between walking speeds and knee flexion angles of people with DS reported good correlations in both centres, 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 than

S group, as for the Padua 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°). Comparing the knee flexion angle over the whole gait cycle in Padua (Figure 3 and 4) and in Antwerp (Figure A.1 and A.2), differences between AC and S were obtained over both stance and swing in Padua and only in the stance phase in Antwerp. This finding has no clear-cut meaning, and we can only speculate on this: differences in the adopted biomechanical models, and specifically in the knee angles calculation, could have affected the results. Indeed, according to the Davis protocol [12], the knee flexion axis was calculated starting from physical markers attached on the patient skin in Padua, whereas the KAD (knee alignment device) was used in Antwerp, which virtually registers the axis during standing, and knee axis reconstruction is then 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 hidden higher expected knee flexions in the AC group during the swing phase [25]. 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 [1,4]. 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 [4], 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 [6] 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 [26]) can reduce excessive tibial anteposition 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%) [27–30]. 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 interest 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)[31] or the WeeFIM (Functional Independence Measure in Children)[32] in children aged 8 or younger, whereas in Antwerp data focused on mobility, based on the Functional Mobility Scale (FMS)[33]. 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.

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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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Table 1

Demographics of the two cohort of people with Dravet in Antwerp and Padova.

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).

Figure 1

Flow chart of the study.

Figure 2

Clinical and Anamnestic data.

Figure 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 centered 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.

Figure 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 centered 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.

Table1

		ANTWERP				PADOVA			
Parameter	**Units**	**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^2	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

Table 2

	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			
	Left StrideTime	*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			

	Left StrideTime	*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

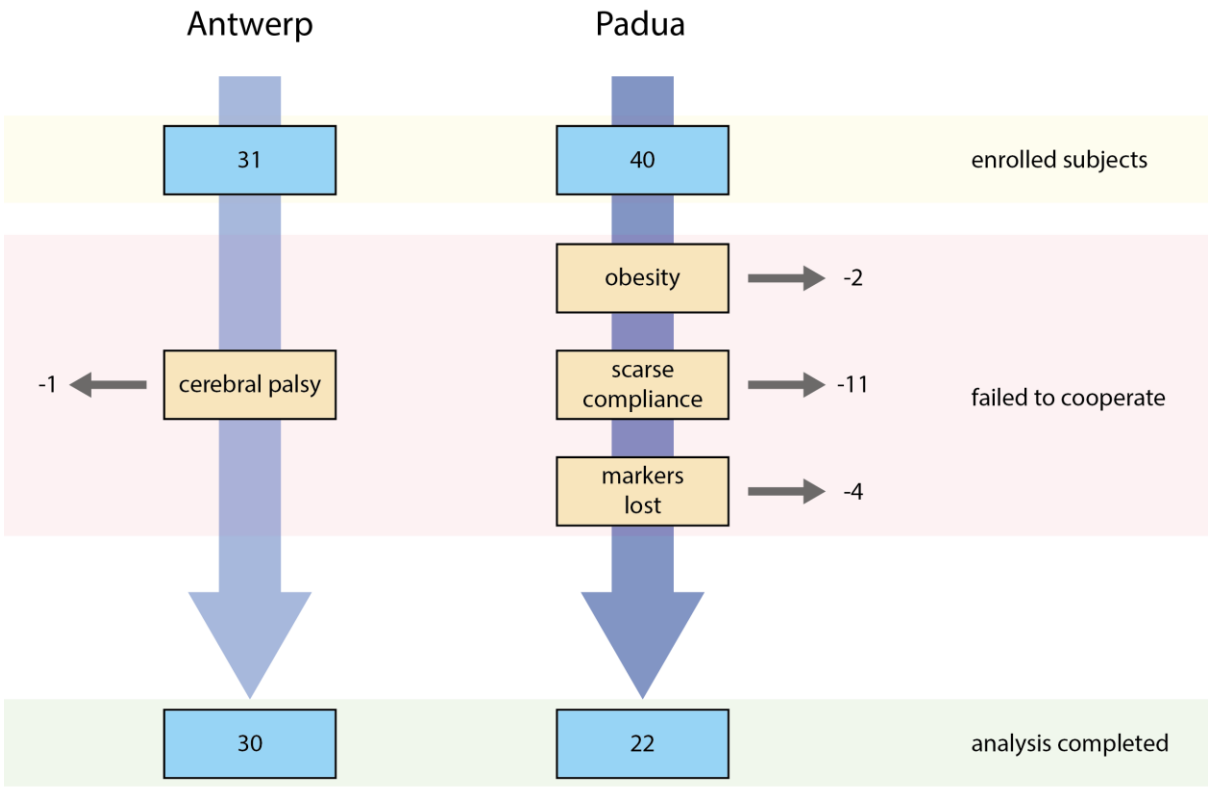
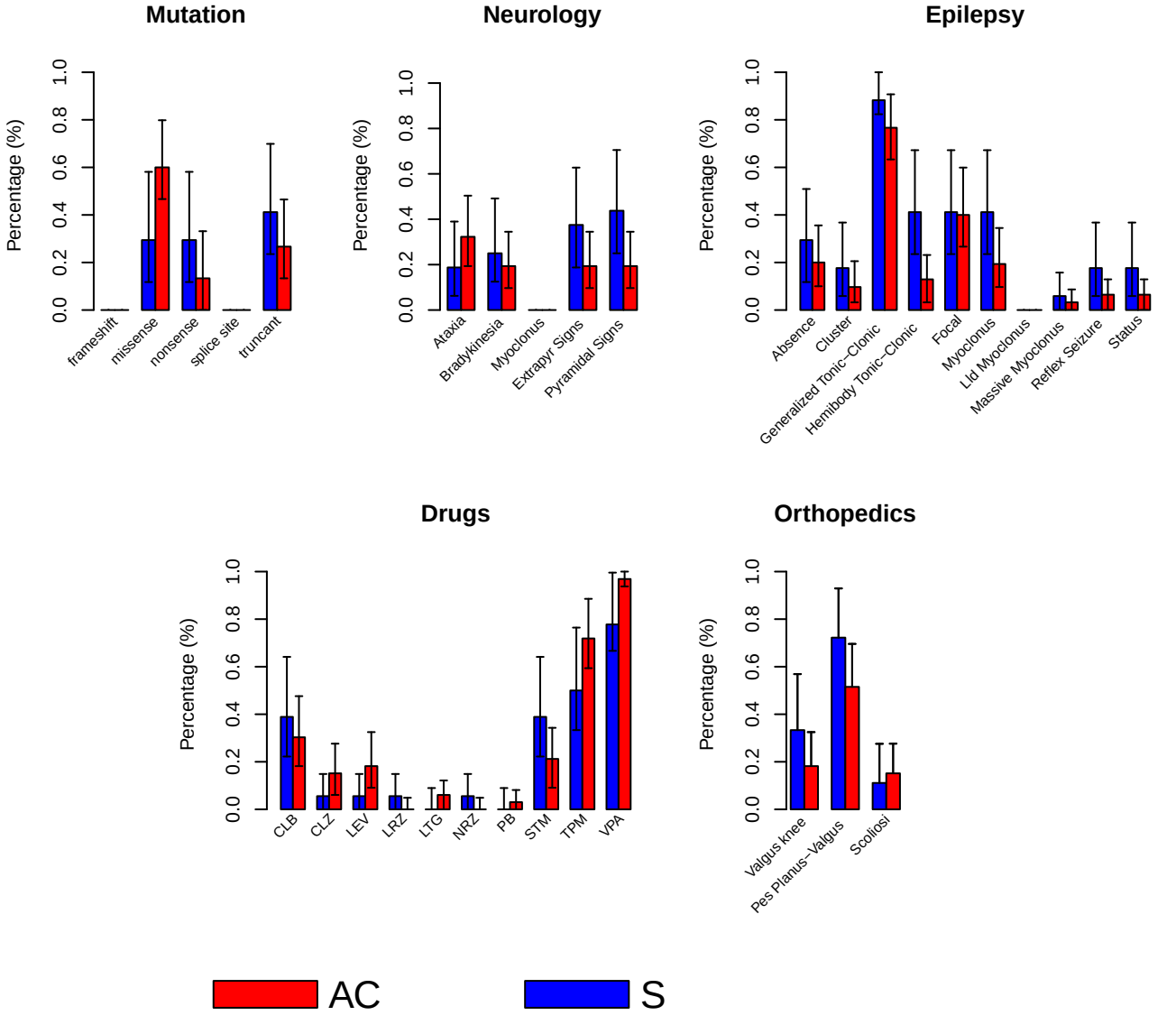

Antwerp
Padua
31
40
enrolled subjects
obesity
-2
-1
cerebral palsy
scarse compliance
-11
failed to cooperate
markers lost
-4
30
22
analysis completed

Figure 1


Mutation
Percentage (%)
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0.4
0.6
0.8
1.0
frameshift
missense
nonsense
splice site
truncant
Neurology
Ataxia
Bradykinesia
Myoclonus
Extrapyr Signs
Pyramidal Signs
Epilepsy
Absence
Cluster
Generalized Tonic−Clonic
Hemibody Tonic−Clonic
Focal
Myoclonus
Lid Myoclonus
Massive Myoclonus
Reflex Seizure
Status
Drugs
CLB
CLZ
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AC
S

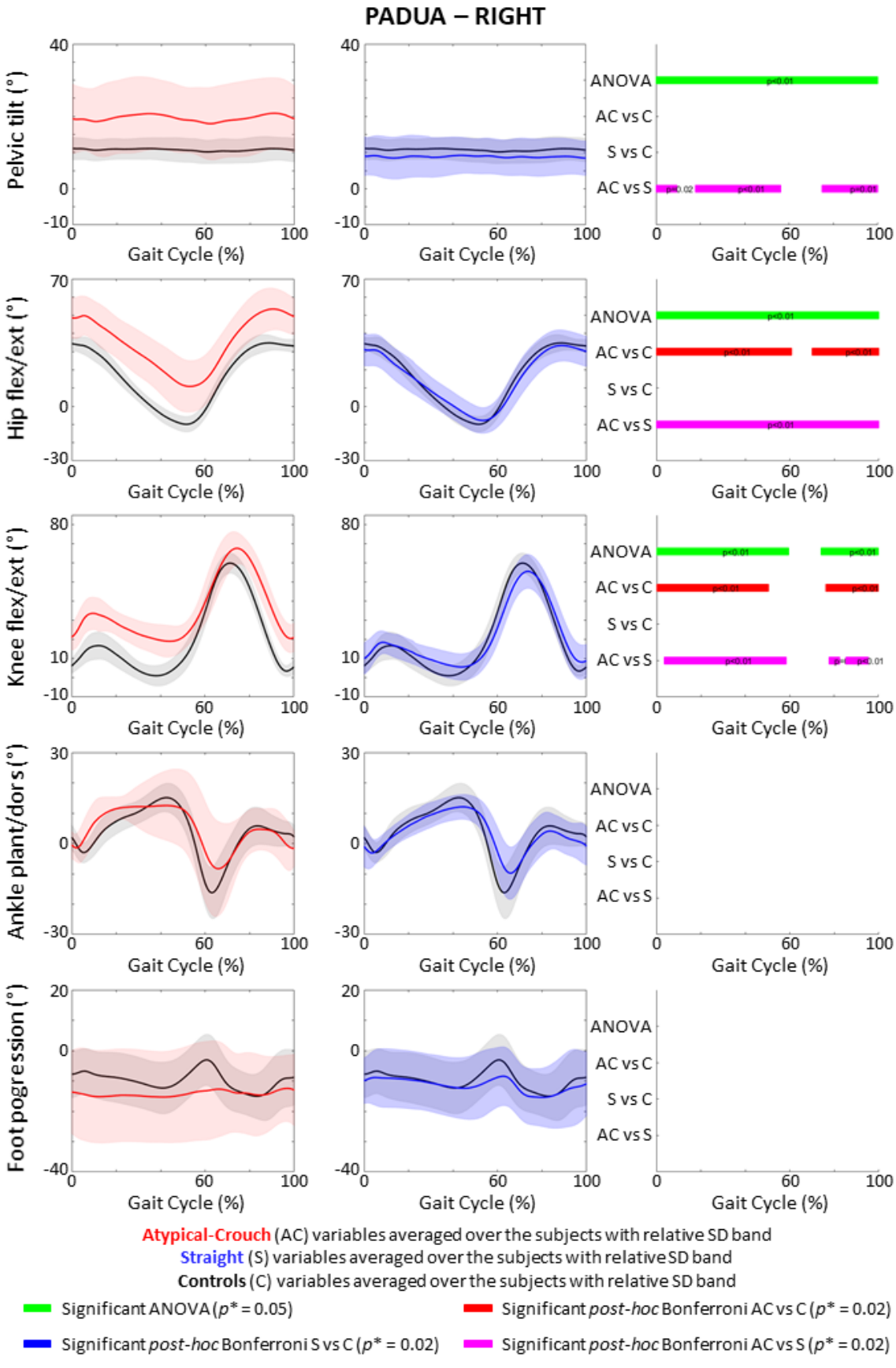

PADUA – RIGHT
Pelvic tilt (°)
Hip flex/ext (°)
Knee flex/ext (°)
Ankle plant/dors (°)
Foot progression (°)
Gait Cycle (%)
ANOVA
AC vs C
S vs C
AC vs S
Atypical-Crouch (AC) variables averaged over the subjects with relative SD band
Straight (S) variables averaged over the subjects with relative SD band
Controls (C) variables averaged over the subjects with relative SD band
Significant ANOVA (p* = 0.05)
Significant post-hoc Bonferroni AC vs C (p* = 0.02)
Significant post-hoc Bonferroni S vs C (p* = 0.02)
Significant post-hoc Bonferroni AC vs S (p* = 0.02)

Figure 3

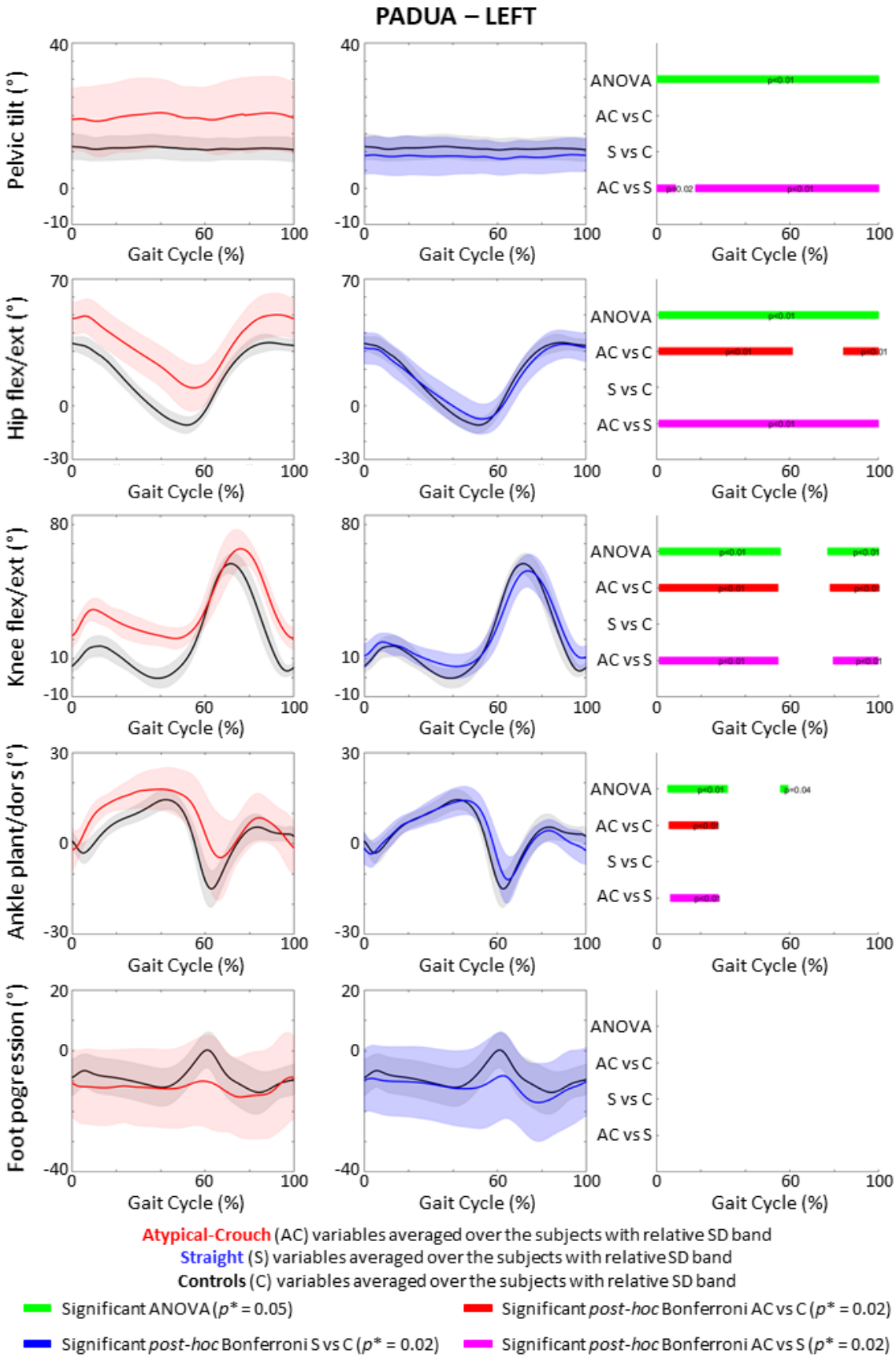

PADUA – LEFT
Pelvic tilt (°)
Hip flex/ext (°)
Knee flex/ext (°)
Ankle plant/dors (°)
Foot progression (°)
Gait Cycle (%)
ANOVA
AC vs C
S vs C
AC vs S
Atypical-Crouch (AC) variables averaged over the subjects with relative SD band
Straight (S) variables averaged over the subjects with relative SD band
Controls (C) variables averaged over the subjects with relative SD band
Significant ANOVA (p* = 0.05)
Significant post-hoc Bonferroni AC vs C (p* = 0.02)
Significant post-hoc Bonferroni S vs C (p* = 0.02)
Significant post-hoc Bonferroni AC vs S (p* = 0.02)

Figure 4

Supplemental materials

Table A.1 – Definition of the main gait phases and spatio-temporal parameters.

Quantity	Definition
Foot strike	Instant at which the foot hits the ground during walking.
Foot off	Instant at which the foot completely lifts from the ground.
Stride or Gait Cycle	Defined between two subsequent foot strikes of the same limb. Its duration is expressed in seconds (s).
Step	Defined between a foot strike and the subsequent foot strike of the contralateral limb (half of the gait cycle). Its duration is expressed in seconds (s) and gait cycle percentage (%GC).
Stance	Period of time with the foot in contact with the ground (from a foot-strike to a foot-off). It is normally the 60% of the gait cycle. Its duration is expressed in seconds (s) and gait cycle percentage (%GC).
Swing	Period of time with the foot not in contact with the ground (from a foot-off to a foot-strike). It is normally the 40% of the gait cycle. Its duration is expressed in seconds (s) and gait cycle percentage (%GC).
Single support	Period of stance with the ipsilateral limb on swing. It is normally the 50% of the gait cycle. Its duration is expressed in seconds (s) and gait cycle percentage (%GC).
Double support	Period of stance with both feet in contact with the ground. It is normally the first 10% of the gait cycle. Its duration is expressed in seconds (s) and gait cycle percentage (%GC).
Stride length	Length between the foot at two subsequent foot-strike of the same limb. It is normally measured in meters (m) and normalized with respect to the subject height (%H).
Step width	Length between the feet at two subsequent foot-strikes of the two limbs. It is normally measured in meters (m) and normalized with respect to the subject height (%H).
Walking speed	The velocity the subject is walking at. It is normally expressed in both meter per seconds (m/s) and normalized with respect to the subject height (%H/s).

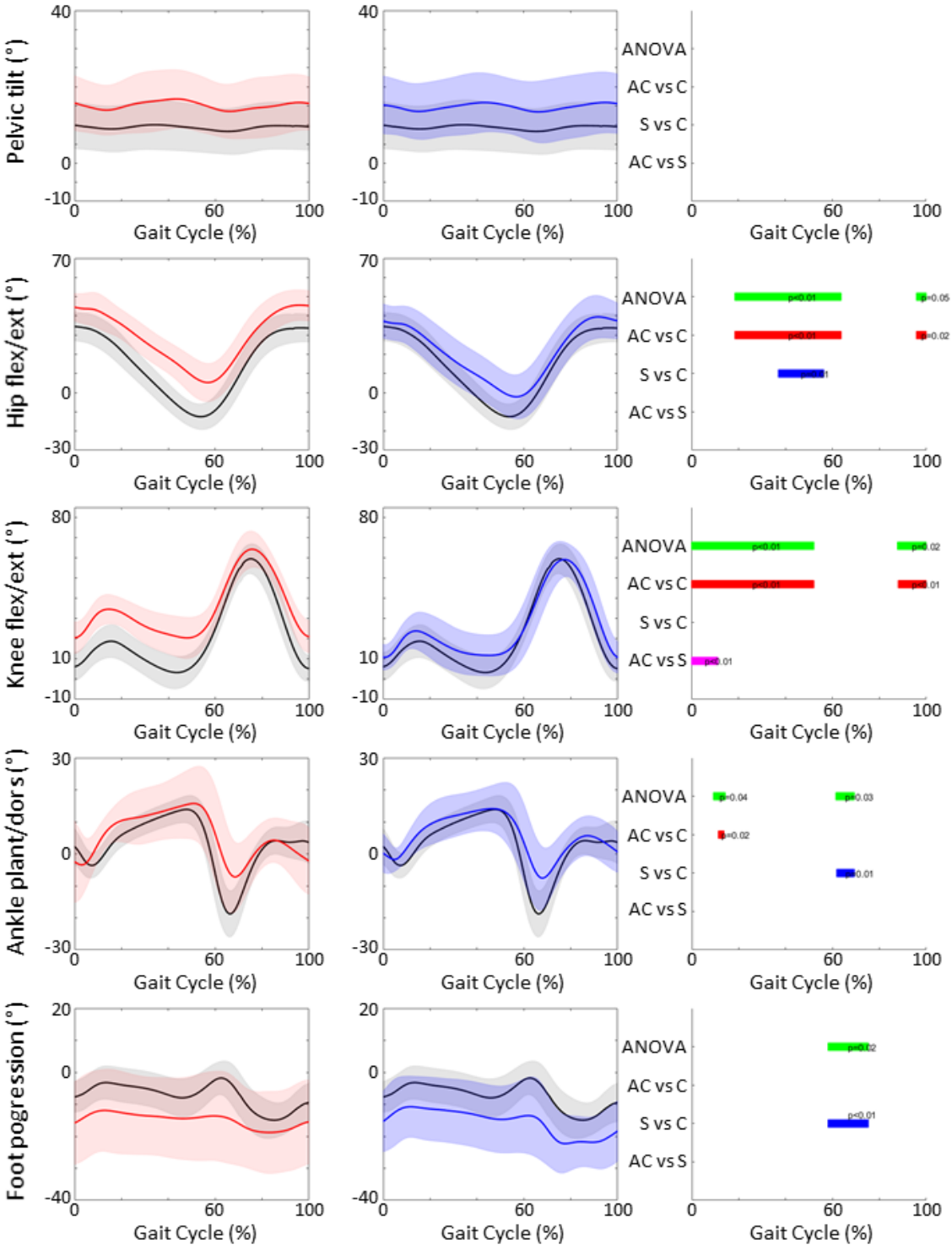


Figure A.1 – Kinematics obtained on the sagittal plane for the right side for controls (bands in black), atypical crouch (red) and straight (blue). Data recorded at the University of Antwerp Movement Analysis laboratory. Bands are centred on the average curve and encompass 1 standard deviation. Differences 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.

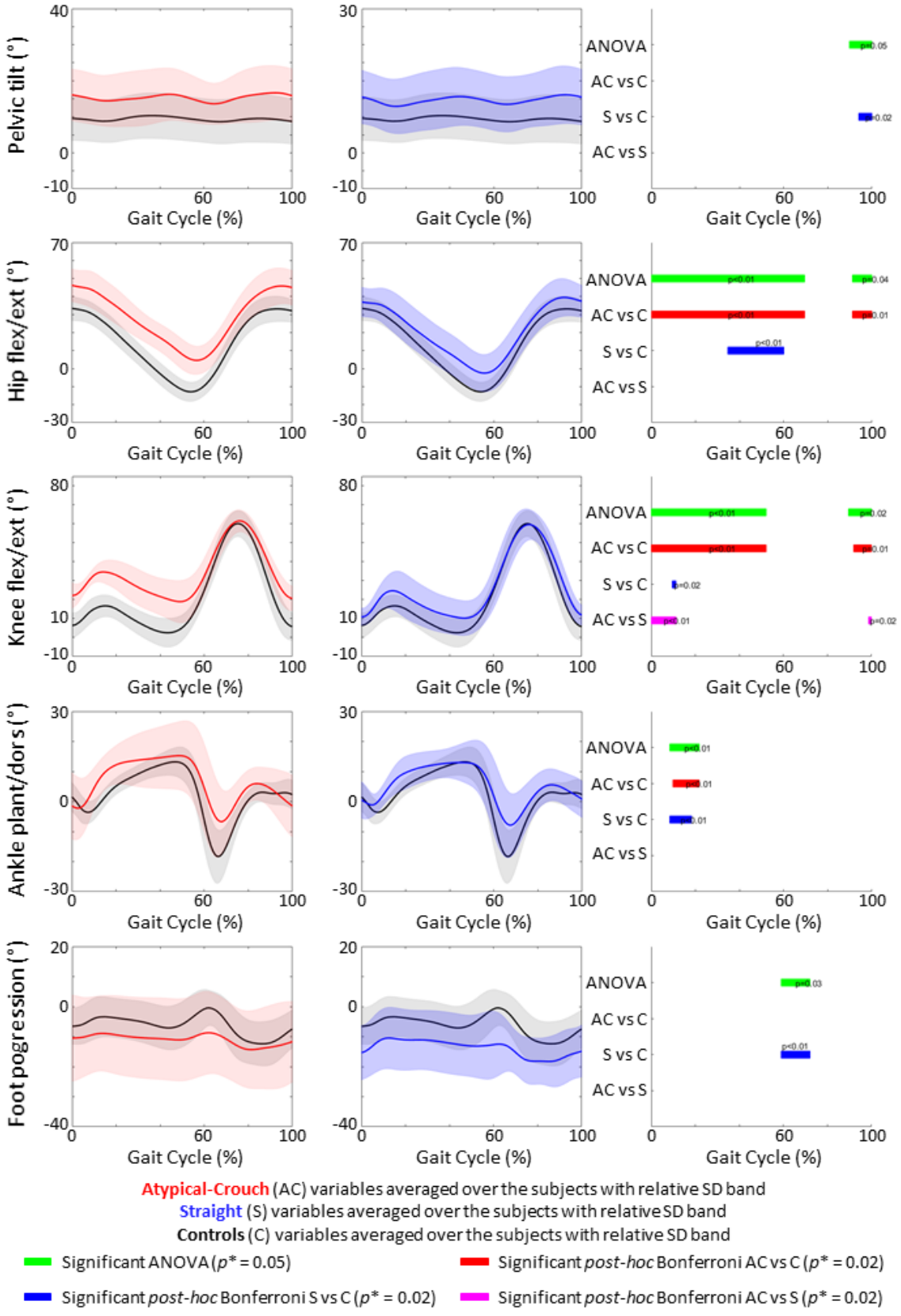
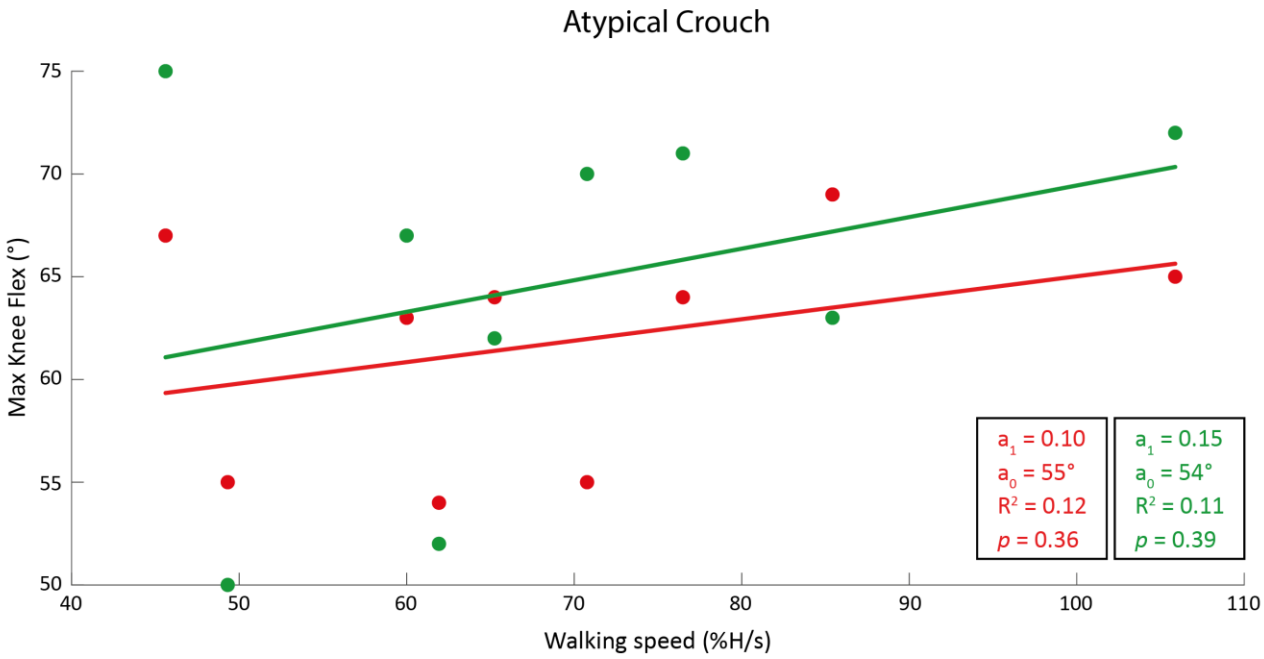


Figure A.2 – Kinematics obtained on the sagittal plane for the left side for controls (bands in black), atypical crouch (red) and straight (blue). Data recorded at the University of Antwerp Movement Analysis laboratory. Bands are centred on the average curve and encompass 1 standard deviation. Differences 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.



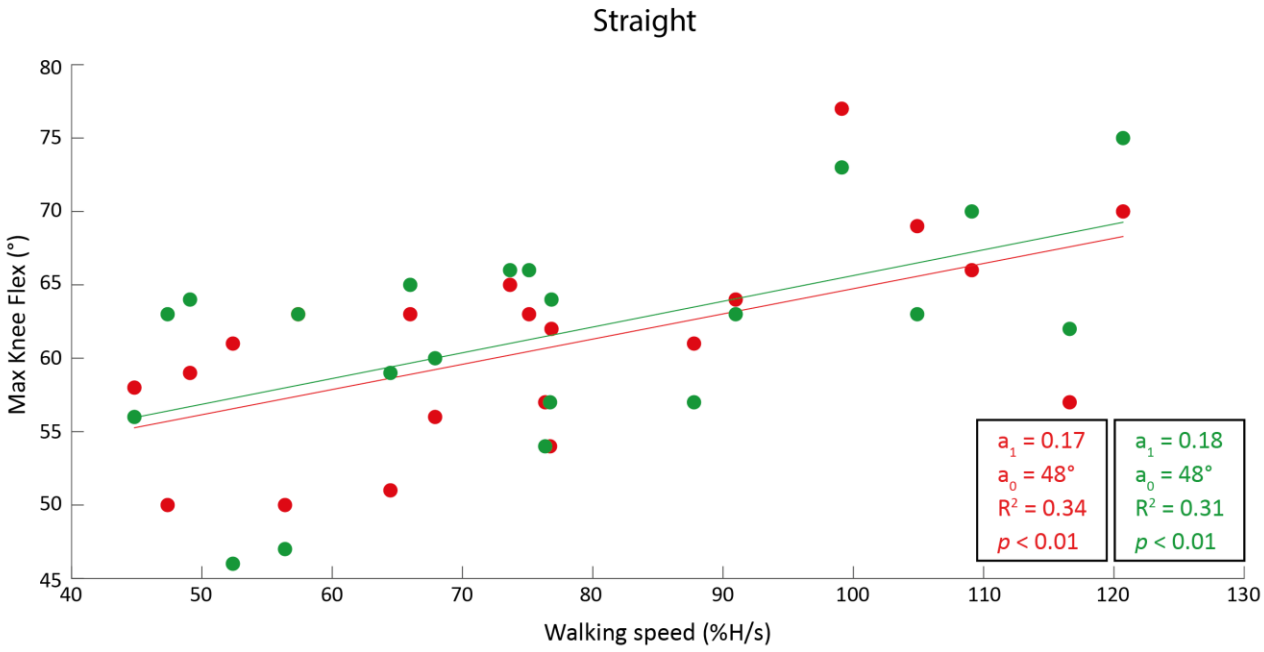


Figure A.3 – Correlation between normalized walking speed and maximum knee flexion angle for the patients enrolled in Antwerp and classified as AC (atypical-crouch) and S (straight). Red lines, dots and parameters refer to the left limb; whereas green plots refer to the right limb. The box shows the regression coefficients (a1, a0 and R2) and the relevant significance of the linear model (p-value lower than 0.05 give significant correlation).

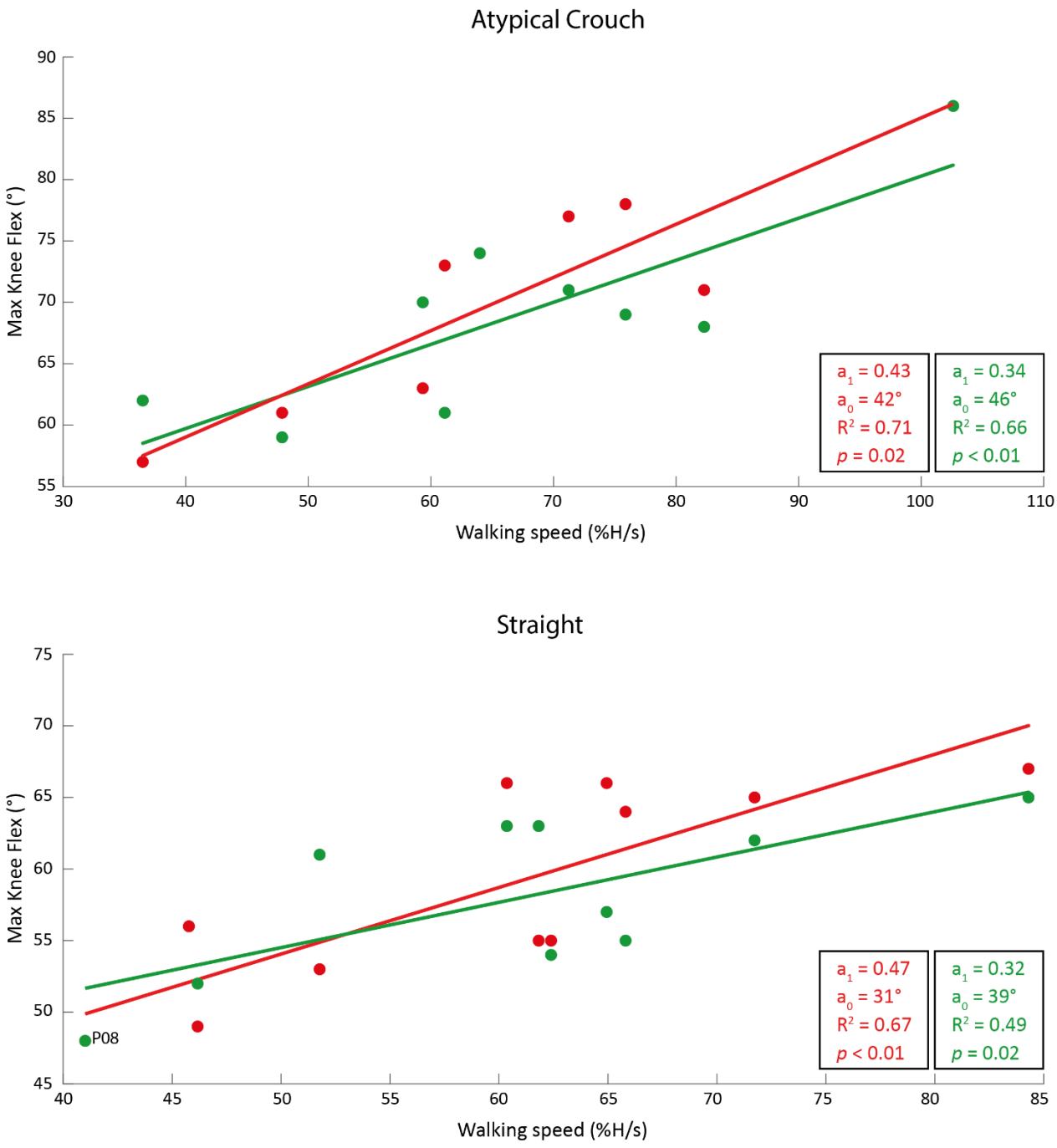


Figure A.4 – Correlation between normalised walking speed and maximum knee flexion angle for the patients enrolled in Padova and classified as AC (atypical-crouch) and S (straight). Red lines, dots and parameters refer to the left limb; whereas green plots refer to the right limb. The box shows the regression coefficients (a1, a0 and R2) and the relevant significance of the linear model (p-value lower than 0.05 give significant correlation).