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Dynamic balance assessment during gait in children with Down and Prader-Willi syndromes using inertial sensors

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ABSTRACT

Down (DS) and Prader-Willi (PWS) syndromes are chromosomal disorders both characterized by obesity, ligament laxity, and hypotonia, the latter associated with gait instability. Although these shared features may justify a common rehabilitation approach, evidence exists that adults with DS and PWS adopt different postural and walking strategies. The development of an instrumented protocol able to describe these strategies and quantify patients' gait stability in the current clinical routine would be of great benefit for health professionals, allowing them to design personalized rehabilitation programs. This is particularly true for children with DS and PWS, where motor development is dramatically constrained by severe hypotonia and muscle weakness. The aim of this study was, thus, to propose an instrumented protocol, integrated with the clinical routine and based on the use of wearable inertial sensors, to assess gait stability in DS and PWS children.

Fifteen children with DS, 11 children with PWS, and 12 typically developing children (CG) were involved in the study. Participants performed a 10-meter walking test while wearing four inertial sensors located at pelvis, sternum, and both distal tibiae levels. Spatiotemporal parameters (*walking speed*, *stride frequency*, and *stride length*) and a set of indices related to gait symmetry and upper-body stability (*Root Mean Square*, *Attenuation Coefficient* and *Improved Harmonic Ratio*) were estimated from pelvis and sternum accelerations. The Gross Motor Functional Measures (GMFM-88) and Intelligence Quotient (IQ Wechsler) were also assessed for each patient. A correlation analysis among the GMFM-88 and IQ scales and the estimated parameters was then performed.

Children with DS and PWS exhibit reduced gait symmetry and higher accelerations at pelvis level than CG. While these accelerations are attenuated by about 40% at sternum level in CG and DS, PWS children display significant smaller attenuations, thus reporting reduced gait stability, most likely due to their typical "Trendelenburg gait". Significant correlations were found between the estimated parameters and the GMFM-88 scale when considering the whole PWS and DS group and the PWS group alone.

These results promote the adoption of wearable technology in clinical routines to monitor gait patterns in children with DS and PWS: the proposed protocol allows to markedly characterize patient-specific motor limitations even when clinical assessment scores provide similar results in terms of pathology severity. This protocol could be adopted to support health professionals in

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designing personalized treatments that, in turn, could help improving patients' quality of life in terms of both physical and social perspectives.

1. Introduction

Down Syndrome (DS) and Prader-Willi Syndrome (PWS) are chromosomal disorders associated with delayed motor and cognitive development. Down Syndrome is usually caused by an extra copy of chromosome 21 and it has a frequency of one in 700 live births (Korenberg et al., 1994), whereas Prader-Willi Syndrome is a multi-system sporadic disorder caused by the loss of function of genes in a particular region of chromosome 15 and has an incidence of about 1 in 10,000 live births (Cassidy, Schwartz, Miller, & Driscoll, 2012).

The two syndromes present a number of common clinical features, such as obesity, ligament laxity, and severe hypotonia (or low muscle tone) (Bittel & Butler, 2005; Fidler, Hodapp, & Dykens, 2002). On the one hand, obesity has been proven to induce negative effects on daily living activities (Elshemy, 2013; Vismara et al., 2007). On the other hand, ligament laxity contributes to the development of a variety of podiatric anomalies such as excessive foot pronation (Concolino, Pasquzzi, Capalbo, Sinopoli, & Strisciuglio, 2006), whereas hypotonia, which is the most common form of neuromuscular pathology in these populations, has been proven to be a major cause of unpaired postural control and gait instability (Davis & Kelso, 1982). In addition, hypotonia is closely related to a delay in achieving motor development milestones as observed in children with DS (Malak, Kostiukow, Krawczyk-Wasielewska, Mojs, & Samborski, 2015) and PWS (Cassidy et al., 2012), where motor functions such as sitting, standing, and walking, arise at a doubled age, on average, with respect to typical developing children. In this framework, from a biomechanical point of view, the observation of the main motor features and the monitoring of their evolution over time can largely support the assessment of the patient's functional limitations. This may impact on the design of pathology-specific rehabilitative interventions and on the clinical assessment of their effects (Cimolin & Galli, 2014).

Gait analysis literature about DS offers a quite extensive research about postural and gait patterns of adults (Galli, Cimolin, Pau, Costici, & Albertini, 2014; Galli, Rigoldi, Brunner, Virji-Babul, & Albertini, 2008) and children (Caselli, Cohen-Sobel, Thompson, Adler, & Gonzalez, 1991; Elshemy, 2013; Rigoldi, Galli, Mainardi, Crivellini, & Albertini, 2011). A prolonged hip flexion has been observed in DS population throughout the gait cycle, probably to reduce the external knee flexion moment, together with a reduction in hip range of motion and a consequent decrease in stride length (Galli et al., 2008). In children and adolescents, Caselli and colleagues (Caselli et al., 1991) described patients with DS as having a "Chaplinesque" gait, characterized by external rotation of the hips and increased knee flexion. Again, when considering children and adolescents, the motor schemes adopted by DS patients differ with respect to those observed in their healthy peers (Rigoldi, Galli, & Albertini, 2011): specifically, hypotonia impacts on the early appearance of protective reactions, necessary for the development of balance strategies. Furthermore, individuals with developmental disabilities exhibit increased medio-lateral sway when compared to healthy participants, a parameter able to predict postural instability (Maki, Holliday, & Topper, 1994).

Only few studies focused on PWS motor abilities, all considering adult patients (Cimolin et al., 2014; Cimolin, Galli, Vismara, et al., 2011; Vismara et al., 2007). Abnormal gait patterns, postural disability, and a delay in gait maturation have been reported in PWS (Cimolin et al., 2014), as well as reduced walking speed and stride length (Cimolin, Galli, Vismara, et al., 2011; Vismara et al., 2007).

DS and PWS do share several clinical and functional features and, due to those common aspects, therapeutic approaches may share some common bases (Cimolin, Galli, Grugni, et al., 2011). Despite that, evidence exists that these two populations adopt different postural (Cimolin, Galli, Grugni, et al., 2011) and walking strategies (Cimolin et al., 2010). Specifically, the literature reports that, during walking, PWS adults are characterized by longer stance durations, greater pelvic and hip ranges of motion in the frontal plane, as well as a reduced hip stiffness with respect to DS population (Cimolin et al., 2010). These findings suggest that the existing differences between the two syndromes are not adequately considered in the design of rehabilitation programs that should be tailored to the patient-specific motor limitations. This is of particular importance in children with intellectual disability, where motor problems are most striking and motor development is dramatically constrained by severe hypotonia and muscle weakness (Eiholzer et al., 2008). This circumstance is burdened by the current limited use of motion analysis approaches in the real clinical practice, where camera-based systems, although considered the gold standard methodology, are hard to be included in the current assessment routines to guide the design of rehabilitation programs.

From an instrumental point of view, previous studies dealing with gait and postural analysis of DS and PWS patients relied on the use of the abovementioned camera-based systems. These systems provide a large set of gait parameters, but despite major convenience regarding accuracy, expensive laboratory equipment, lengthy set-up, and time-consuming post-processing procedures are required (Cimolin & Galli, 2014).

A current trend in human motion analysis is represented by miniaturized wireless motion sensors, presenting the advantage of reproducing a testing condition more similar to that of daily living (Tamburini et al., 2018). Focusing on gait stability, defined as the capacity to maintain upright balance by minimizing upper body oscillations during walking (Cappozzo, 1981), sensor networks were fruitfully used to assess gait patterns in children (Summa et al., 2016). Although this technology has already been considered in the analysis of upper body accelerations in children with intellectual disability (Iosa et al., 2014), the authors limited their analysis to a single-sensor monitoring at lower trunk level, thus preventing possible investigations about how accelerations propagate through the

upper body as a result of specific motor strategies actuated by pathology-groups (Bergamini et al., 2017; Summa et al., 2016). Finally, previous studies remarked the difficulty to test children with intellectual disability (Iosa et al., 2014) and to perform between-pathologies comparisons. As a result, a lack of knowledge and tools exists concerning the implementation of pathology-specific treatments.

In this framework, the aim of this study was to propose an in-field protocol based on the use of a multi-sensor approach in order to assess and compare gait patterns of children with DS and PWS with respect to typically developing children. The outcome of the present study could allow health-professionals to develop and evaluate the efficacy of pathology-specific and personalized re-habilitation treatments.

2. Methods

2.1. Ethics statement

All participants and their parents, or legal guardians, provided written informed consent according to the declaration of Helsinki. The study was approved by the Local Independent Ethics Committee of the Santa Lucia Foundation.

2.2. Participants

Fifteen children with Down Syndrome (DS) (6 males and 9 females; Body Mass Index (BMI) range: 15.2–24.0 kg/m^2, age range: 2.8–11.7 years), 11 children with Prader-Willi Syndrome (PWS) (7 males and 4 females; BMI range: 12.9–32.4 kg/m^2, age range: 2.7–10.1 years), and 12 typically developing children (CG) (6 males and 6 females; BMI range: 11.3–23.6 kg/m^2, age range: 3.7–11.0 years) were involved in the study. Inclusion criteria for DS and PWS children were the absence of comorbidities, the ability to understand and follow the instructions given to them and to walk freely without any support or assistive mobility device (Gross Motor Function Scale Classification System < 3). Inclusion criteria for CG subjects were the absence of neurological, orthopedic or motor disorders.

To take into consideration the known variability of gait parameters in young children, a subject by subject matching was performed through individual matching process (Pearce, 2016), using age as confounding factor. DS and PWS children were recruited from the Santa Lucia Foundation where they were undergoing strict guidance for control of feeding obsession. Leg length was measured as the distance between the greater trochanter and lateral malleolus while standing. Demographic characteristics of participants are reported in Table 1. No statistically significant difference was found among the three groups for what concerns age, stature, leg length, mass, and BMI (one-way ANOVA, $p > 0.05$). Specifically, careful attention was paid in matching both mass and BMI across groups in order to prevent misinterpretations due to overweight/obesity as origins of possible motor deviations.

In addition, both DS and PWS groups were evaluated by a trained physiotherapist, using the Gross Motor Functional Measures (GMFM-88) scale, as originally designed by (Russell et al., 1989), and the Gross Motor Function Scale Classification System (GMFCS, Palisano et al., 1997), and by a psychologist, using the Intelligence Quotient (IQ) Wechsler scale. The GMFM-88 scale consists of 88 items grouped in five dimensions: *A)* lying and rolling, *B)* sitting, *C)* crawling and kneeling, *D)* standing, and *E)* walking, running, and jumping. This scale has been widely used to measure functional mobility in children with DS (Malak, Kotwicka, Krawczyk-Wasielewska, Mojs, & Samborski, 2013) and its validity and reliability has been proven by (Adair, Said, Rodda, & Morris, 2012). Each GMFM-88 item was scored by observation on a 4-point ordinal scale: 0 indicates that a child did not initiate the task and 3 that a child completed the task, with a score for each one of the five dimensions expressed as a percentage (Russell et al., 1989; Wang & Yang, 2006). The total score of the GMFM-88 values was computed as the mean of these five percentages. In the present study, the focus was placed on this total score and on the percentage score of dimension E, specifically addressing locomotion. Assessment of the degree of

Table 1
Participants anthropometric characteristics. The groups were homogeneous with respect to the listed parameters ($p > 0.05$).

Parameters		CG	PWS	DS
Participants		12	11	15
Gender [males %]		50	63	40
Age [years]	Mdn	6.10	5.30	6.63
	IQR	4.63	6.00	8.20
Stature [m]	Mdn	1.13	1.11	1.09
	IQR	0.26	0.36	0.39
Leg Length [m]	Mdn	0.55	0.57	0.58
	IQR	0.19	0.14	0.15
Mass [kg]	Mdn	20.0	18.0	22.0
	IQR	10.8	18.9	10.2
BMI [kg/m^2]	Mdn	15.8	17.0	17.5
	IQR	1.65	5.34	3.83

disability was performed according to the Gross Motor Function Scale Classification System (GMFCS), based on five levels of disability (first level shows minimal motor limitations, fifth level shows complete inability to perform autonomous motor activities) (Palisano et al., 1997). GMFCS takes into account the chronological maturity in different age stages (up to 2 years, 2–4 years, 4–6 years and 6–12 years) by exploring five different levels of disability, as also reported by (Delalić, Kapidžić-duraković, & Tahirović, 2010) in children with cerebral palsy. The interrater reliability for GMFCS in children with cerebral palsy and Down syndrome has been reported by (Bodkin, Robinson, & Perales, 2003). As concerns the IQ Wechsler scale, the fourth edition (WISC-IV) was used: some of the WISC-IV subtests start at predetermined items according to the child's age and the highest possible score was 160 (Kaufman, Flanagan, Alfonso, & Mascolo, 2006).

2.3. Experimental protocol

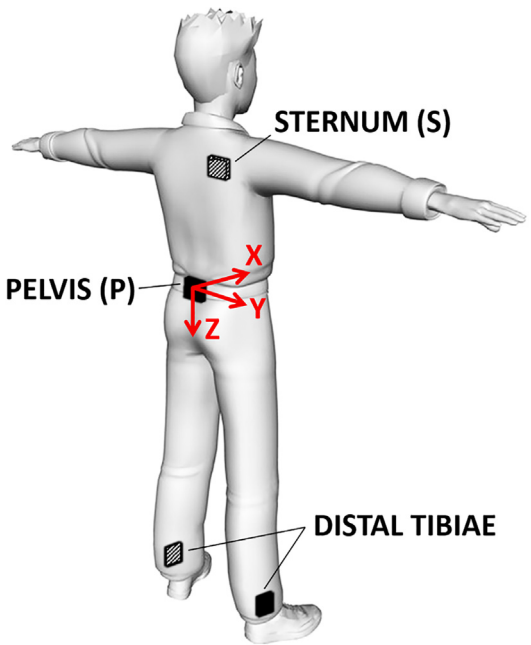
Each participant performed three repetitions of the 10-meter walking test (32.8 feet). Standing on a line marked on the floor, he/she was instructed to walk straight at a self-selected speed until reaching the finish line, whilst focusing on a target set at eye level located at the end of the walkway.

Four Inertial Measurement Units (IMUs) (Opal, APDM Inc., Portland, Oregon, USA) were used to collect 3D linear accelerations and angular velocities. Each unit included tri-axial accelerometers and gyroscopes ($\pm$ 6 g with g = 9.81 $m \cdot s^{-2}$, and $\pm$ 1500 $deg \cdot s^{-1}$ of full-range scale, respectively; accelerometer sensitivity: 220 mV/g) and provided the measured quantities with respect to a unit-embedded system of reference. To assess upper-body stability, two units were placed on the participants' upper-body: one on the center of the sternum (S) and one at L4/L5 level, slightly above the pelvis (P) (Fig. 1). The other two units were located on both distal tibiae (lateral malleoli) (Fig. 1) and were used to perform step segmentation. IMUs were attached to the body with Velcro® straps and fixed to avoid oscillations due to soft-tissues. All the devices were electronically synchronized prior to the testing session, and data were transmitted by a wireless radio network to a laptop at a sampling frequency of 128 samples/s.

2.4. Data processing

All data processing was performed using MATLAB® (R2016a, The MathWorks Inc., Natick, MA, USA).

Before each experimental session, IMU accelerometers were calibrated as reported in (Bergamini et al., 2014). To guarantee a repeatable system of reference for all participants, a verticalized frame was used for the upper-body sensors. Each unit frame was rotated (using a time-invariant rigid transformation representing the inclination of the sensor with respect to gravity during the static posture) so as to have an axis aligned to the gravity vector during the initial static posture (Bergamini et al., 2014). Its axes were thus considered to approximate antero-posterior (AP), medio-lateral (ML), and cranio-caudal (CC) anatomical axes. Finally, acceleration



http://www.3dcadbrowser.com/download.aspx?3dmodel=10931

Fig. 1. Location of the four wearable inertial measurement units: one on the center of the sternum (S), one at L4/L5 level, slightly above the pelvis (P), and two units on both distal tibiae (lateral malleoli). The axes orientation of the pelvis (P) and sternum (S) units was the same during the static phase at the beginning of each trial. For the sake of clarity only the orientation of the pelvis unit is depicted (AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal).

signals were low-pass filtered using a 4th-order Butterworth filter at 20 Hz, according to the results of a residual analysis (Winter, 1990). Step segmentation was then performed through a peak-detection algorithm applied to the angular velocities measured around the tibiae ML axes.

The following spatiotemporal parameters were calculated for each 10-meter walking test: average walking speed (*WS* = 10 m/time to complete the test), average stride length (*SL* = 10 m/total number of strides), and stride frequency (*SF* = total number of strides/time to complete the test). The following relevant normalized values of *nWS*, *nSL* and, *nSF* were then calculated as proposed by (Hof, 1996):

$$nWS = \left(\frac{WS}{\sqrt{gl_0}}\right)$$

$$nSL = \left(\frac{SL}{l_0}\right)$$

$$nSF = \left(\frac{SF}{\sqrt{g/l_0}}\right)$$

where g and l_0 correspond to the gravitational acceleration and the leg length, respectively.

The following gait stability parameters were then estimated for each steady-state stride:

- Normalized Root Mean Square (*nRMS*) values of the accelerations at each upper-body level (P and S). Due to the influence of the walking speed on these parameters, they were normalized according to Mizuike and colleagues (Mizuike, Ohgi, & Morita, 2009), dividing the RMS by the squared value of WS and multiplying it by SL. High *nRMS* values are associated with greater acceleration and, hence, decreased stability (Belluscio et al., 2018; Bergamini et al., 2017; Buckley, Galna, Rochester, & Mazzà, 2018; Iosa et al., 2014; Mazzà, Iosa, Pecoraro, & Cappozzo, 2008).
- Attenuation Coefficient between Pelvis and Sternum (*ACPS*) (Mazzà et al., 2008), for each acceleration component (*j*), defined as:

$$ACPS_j = \left(1 - \frac{RMS_jS}{RMS_jP}\right)$$

The coefficient represents the variation of the acceleration from pelvis to sternum. A positive (negative) coefficient indicates an attenuation (amplification) of the accelerations from the lower to the upper level (Belluscio et al., 2018; Bergamini et al., 2017; Buckley, Galna, Rochester, & Mazzà, 2018).

- Improved Harmonic Ratio (*iHR*) (Pasciuto, Bergamini, Iosa, Vannozzi, & Cappozzo, 2017) for each acceleration component (*j*) measured at the pelvis level. This index is a measure of gait symmetry (0% = total asymmetry; 100% = total symmetry) and is based on a spectral analysis of the acceleration signals. It was calculated as follows:

$$iHR_j = \frac{\sum Power\ of\ intrinsic\ harmonics}{\sum Power\ of\ intrinsic\ harmonics + \sum Power\ of\ extrinsic\ harmonics} \cdot 100$$

where harmonics characterizing a perfectly symmetrical gait are named intrinsic and harmonics leading to deviations from the ideal

Table 2
Absolute and normalized spatiotemporal parameters (Walking Speed *WS*, Stride Length *SL*, and Stride Frequency *SF*). The results of the statistical analysis are also reported.

Parameters		CG	PWS	DS	p-value	U-Mann
WS [m/s]	Mdn	0.87	0.86	0.86	0.92	80.0
	IQR	0.27	0.32	0.18		
SL [m]	Mdn	0.91	0.83	0.91	0.88	79.5
	IQR	0.28	0.33	0.20		
SF [strides/s]	Mdn	0.92	1.04	1.09	0.84	78.0
	IQR	0.26	0.52	0.45		
nWS	Mdn	0.34	0.35	0.36	0.88	79.0
	IQR	0.12	0.17	0.10		
nSL	Mdn	1.66[§]	1.30	1.41[§]	0.01[§]	37.5[§]
	IQR	0.52	0.88	0.27		
nSF	Mdn	0.21[§*]	0.26[*]	0.27[§]	< 0.01[*§]	> 25.0[*§]
	IQR	0.05	0.09	0.07		

[§]Differences between CG and DS.
[*]Differences between CG and PWS.

gait are named extrinsic (Belluscio et al., 2018; Bergamini et al., 2017).

2.5. Statistical analysis

Descriptive and inferential statistical analyses were performed using the IBM SPSS Statistics software (v23, IBM Corp., Armonk, NY, U.S.A.). For the indices calculated over each stride, the median (Mdn) and inter-quartile range (IQR) values were computed. The alpha level of significance was set to 0.05. The normal distribution of each parameter and each clinical score was verified using the Shapiro-Wilk test. To investigate if significant differences existed among DS, PWS, and CG for spatiotemporal and gait stability parameters, a One-Way ANOVA was performed for the normal distributed parameters, whereas the Kruskal-Wallis H-test was performed when the data was not normally distributed. When a significant "group" effect was found, pairwise comparisons were analysed through Tukey *post hoc* or Mann-Whitney U tests using the Bonferroni-Holm correction to prevent the inflation of Type I errors. The effect sizes for each significant parameter was also calculated and reported as eta square value (η^2) (Richardson, 2011). To investigate if statistically significant differences existed between PWS and DS for all items of the GMFM-88 scale and for IQ, a Mann-Whitney *U* test was performed. Finally, the Spearman's rank correlation coefficient (ρ) was used to assess the relationship between each estimated parameter and the GMFM-88 values, the fifth dimension (E) of the GMFM-88, and the IQ, both across the total group of DS and PWS children and for each single group

3. Results

The values of the spatiotemporal parameters are reported in Table 2, for each group. Significant differences were found between CG and DS for stride length (*nSL*) (U-Mann = 37.5, p = 0.01, $\eta^2 = 0.25$) and frequency (*nSF*) (U-Mann = 32, p = 0.005, $\eta^2 = 0.30$), as well as between CG and PWS for the *nSF* (U-Mann = 25, p = 0.012, $\eta^2 = 0.28$). No significant differences were found between DS and PWS for spatiotemporal parameters.

The box-plots of gait stability parameters are reported in Fig. 2. Significant differences with large effect sizes were found between CG and DS for the *nRMS* accelerations at pelvis level in the ML direction (U-Mann = 44, p = 0.025, $\eta^2 = 0.19$), for *ACPS* both in the AP direction (U-Mann = 50, p = 0.005, $\eta^2 = 0.14$) and in the CC direction (U-Mann = 26, p = 0.002, $\eta^2 = 0.37$), and for *iHR* in the AP direction (U-Mann = 40, p = 0.01, $\eta^2 = 0.22$). In the comparison between CG and PWS, significant differences were found for *nRMS* at the trunk level in the ML direction (U-Mann = 31, p = 0.031, $\eta^2 = 0.21$), for *ACPS* in the CC direction (U-Mann = 23, p = 0.007, $\eta^2 = 0.31$), and for *iHR* in the AP direction (U-Mann = 21, p = 0.004, $\eta^2 = 0.34$). Furthermore, when comparing DS and PWS, significant differences were found for *ACPS*, both in the AP direction (U-Mann = 43, p = 0.04, $\eta^2 = 0.16$) and in the ML direction (U-Mann = 17, p = 0.001, $\eta^2 = 0.46$).

For what concerns GMFCS scores, almost all DS and PWS children were classified as level 1, while only four participants (2 DS and 2 PWS) were assigned to level 2. In Table 3, GMFM-88 and IQ scores for DS and PWS are reported: no statistically significant difference was found between DS and PWS groups for all items of the GMFM-88 and for the IQ scale ($p > 0.05$).

About correlation analysis performed across the whole group of children with DS and PWS, the GMFM-88 negatively correlated

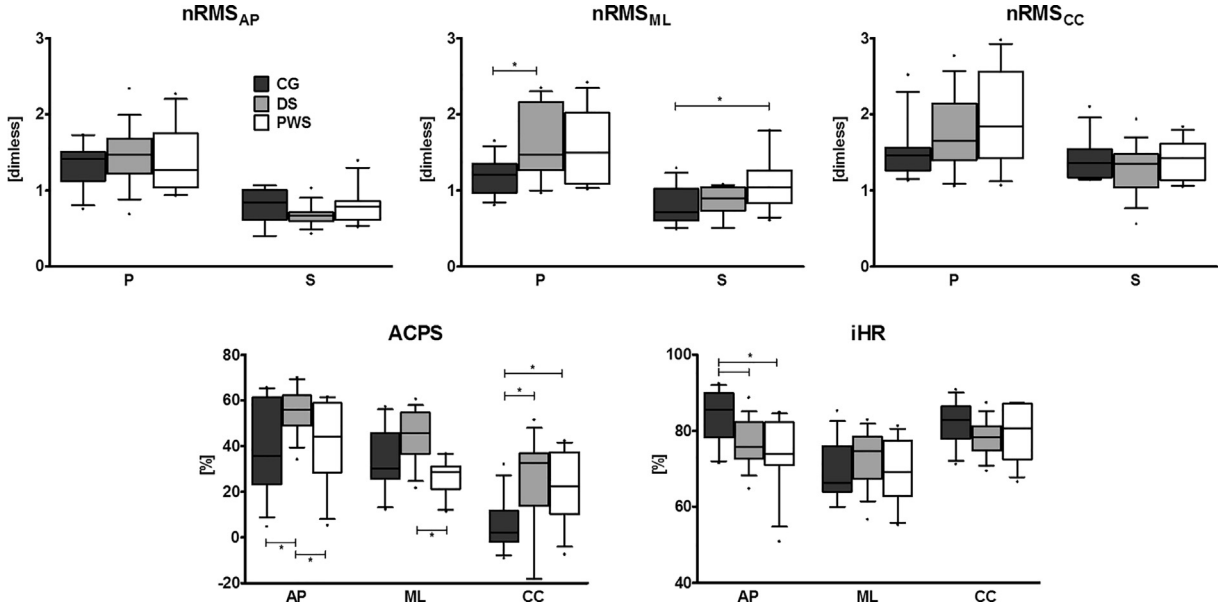


Fig. 2. Normalized RMS values (*nRMS*), attenuation coefficients (*ACPS*), and improved Harmonic Ratio (*iHR*) for Down Syndrome (DS), Prader-Willi Syndrome (PWS) and typical developing children (CG). Medians and interquartile ranges are reported. AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum. The horizontal lines with asterisks (*) indicate statistically significant differences between groups.

Table 3
Median and Inter Quartile Range (Mnd (IQR)) of GMFM-88 and IQ scores for PWS and DS children. The results of the statistical analysis are also reported.

	PWS	DS	p-value	U-Mann
GMFM-88				
A	100.0 (0.0)	100.0 (0.0)	0.80	77.0
B	98.3 (6.7)	100.0 (0.4)	0.06	46.0
C	92.8 (20.2)	95.4 (26.8)	0.61	72.5
D	89.7 (49.9)	87.1 (14.1)	0.61	72.5
E	68.0 (64.3)	67.3 (28.8)	0.36	64.0
Total	89.0 (45.0)	91.5 (25.0)	0.38	65.5
IQ	62.0 (40.5)	53.5 (23.7)	0.10	37.0

with *nSF* ($\rho = -0.510$, $p = 0.008$) and *nRMS* at pelvis level in the AP direction ($\rho = -0.399$, $p = 0.04$), and positively correlated with *iHR* in the AP direction ($\rho = 0.407$, $p = 0.039$). The dimension E of the GMFM-88 negatively correlated with *nSF* ($\rho = -0.520$, $p = 0.006$), and *nRMS* at pelvis level both in the AP direction ($\rho = -0.424$, $p = 0.031$) and in the ML direction ($\rho = -0.406$, $p = 0.040$). Conversely, it positively correlated with *iHR* in the AP direction ($\rho = -0.452$, $p = 0.021$). No significant correlation was found between the estimated gait parameters and the IQ scale. When performing separate correlation analysis in each single DS and PWS group, results show that the previous correlation pattern remains unaltered only in the PWS group. Conversely, the DS group exhibited only one significant correlation between the dimension E of the GMFM-88 and *nSF* ($\rho = -0.52$, $p = 0.047$). In addition to previously reported results, the PWS group shows positive correlations between the IQ scale and both *ACPS* ($\rho = 0{,}68$ $p = 0.045$) and *iHR* in the ML direction ($\rho = 0{,}73$ $p = 0.026$).

4. Discussion

The present study responds to a clinical query concerning possible differences in gait strategies in children with Down (DS) and Prader-Willi (PWS) syndromes: a multilevel inertial sensor protocol was proposed to characterize motor patterns in these populations when compared to age-matched children with typical development (CG).

The results of the present study showed that, when compared to CG, both DS and PWS children display altered walking strategies, as highlighted by conventional gait analysis studies on adult participants (Cimolin et al., 2010; Rigoldi et al., 2011). It is important to consider that the obtained results are not influenced by either children's walking speed or BMI, which were similar in the three groups ($p > 0.05$). This last aspect is of paramount importance as it allows the exclusion of walking speed and obesity as origins of the motor deviations displayed by the analyzed sample groups, thus allowing to link the observed differences to each of the two syndromes.

The results of spatiotemporal parameters show that both DS and PWS participants displayed reduced stride length and an increased stride frequency. These results are in agreement with the existing literature about adult patients (Cimolin, Galli, Vismara, et al., 2011; Galli et al., 2008; Vismara et al., 2007) and suggest that a cautious and altered gait is observed also in young patients, probably aiming at maintaining balance and stability. The obtained smaller values in spatiotemporal parameters are likely related to hypotonia and ligament laxity (Elshemy, 2013), two hallmarks characterizing both DS and PWS children.

When investigating accelerations and how they propagate through the upper body, both DS and PWS groups showed differences in gait stability parameters, when compared to CG. In fact, a clear trend was observed with both syndromes being characterized by greater accelerations at the pelvis level and a decreased attenuation of the accelerations from the pelvis to the sternum, as already observed in other pathological populations (Bergamini et al., 2017; Summa et al., 2016). These results indicate a reduced gait stability, probably caused by the combination of hypotonia, ligament laxity and, for DS children, by the typical configuration of their pelvic girdle, characterized by a deeper acetabulum and a decreased acetabular angle (Cimolin et al., 2010; Elshemy, 2013). The so-called "mongol pelvis", in fact, entails a limited hip excursion in DS adults, that may account for shorter steps and slower walk when compared to PWS adults (Cimolin et al., 2010). These aspects markedly characterize each specific syndrome and were pointed up by the sensor-based approach even when the traditional clinical assessment scores classified for a similar severity. Therefore, the adoption of wearable assessment tools could represent an added value in the clinical pathway and could support clinicians in designing *ad hoc* treatments.

When comparing the gait patterns displayed by the two syndromes, PWS children presented a reduced attenuation of the accelerations from the pelvis to the sternum, differing from the DS group which exhibited greater attenuation values, behaving similarly to CG in the ML direction. Differences between syndromes are particularly evident when considering the AP and ML directions and could be related to the "Trendelenburg gait", typical of PWS motor behavior (Van Iersel & Mulley, 2004). These large accelerations at upper body levels may interfere with the normal information processing, thus weakening the control of dynamic balance during gait (Summa et al., 2016). This result corroborates previous findings in adults (Cimolin et al., 2010) and demonstrates that different motor patterns can be observed also in children affected by the two considered chromosomal syndromes.

When considering the results of the clinical assessment (total score of the GMFM-88 values, dimension E of the GMFM-88, and IQ), none of the administered scales discriminated between the two populations. For what concerns the GMFCS scale, according to the adopted inclusion criteria, children involved in this study belong either to level 1 or 2. It has to be mentioned that a GMFCS level

higher than 2 implies the use of an assistive mobility device, which could have affected the upper body acceleration outcomes.

Concerning the relationship between sensor-based parameters and traditional clinical outcomes, on the one hand strong correlations were found with the GMFM-88 and the GMFM-88 (E) clinical scores when considering the whole group of children with DS and PWS. Specifically, as the GMFM-88 decreases (i.e. as the severity of the pathology increases), *nSF* and *nRMS*, in both AP and ML directions, increase, whereas *iHR* in the AP direction decreases, as it could be expected. On the other hand, interesting results have been found when performing separate correlation analysis by splitting DS and PWS: the correlation results obtained when the analysis was performed across the total group seem to be essentially attributable to the PWS group. In addition, PWS shows a positive correlation between the IQ and two sensor-based parameters, i.e. *ACPS* and *iHR*. Since both stability and symmetry parameters are positively associated with high-level motor competences, this result corroborates previous findings about the existing relationship between motor and cognitive performance in children with/without intellectual disability (Jabourian et al., 2014; Schott & Holfelder, 2015). Conversely, for the DS population, only the normalized step frequency proved to be correlated to GMFM-88 (dimension E).

Overall, therefore, our findings support the adoption of integrated approaches to dynamic balance assessment, providing clinicians with additional and quantitative information related to gait stability and symmetry. However, in the DS population, the relationship between the GMFM-88 and IQ scales with both spatiotemporal and gait stability parameters is not fully delineated yet. Further investigation is needed to clarify the relationship between clinical scores and sensor-based parameters, possibly increasing sample size and considering PWS and DS groups that are more representative of all clinical score spans.

The main limitation of this work is the wide age range of participants, which highly affects gait variability: in this work, the issue was managed by participants' age matching process (Pearce, 2016). Future researches could consider the use of wearable technologies to support home-monitoring in daily life contexts to deeply investigate how gait stability and symmetry indices are related to typical clinical features and to the quality of life of PWS and DS populations.

5. Conclusions

Children with DS and PWS did not show adequate upper body stabilization as compared to their healthy pairs, probably due to ligament laxity and hypotonia. Furthermore, PWS children adopt different motor strategies with respect to DS during locomotion. Since children affected by these two pathologies are often treated using the same approaches, the results of the present study may help clinicians to delineate a more complete and, most importantly, patient-specific, clinical picture. Therefore, the proposed protocol could support health professionals in designing personalized treatments that, in turn, would help improving patients' quality of life in terms of both physical and social perspectives. Finally, the adopted multi-sensor approach allows tests to be performed in an outdoor environment like that of normal daily living, and to obtain information that can be used alongside traditional clinical scales.

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