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Anticipatory postural adjustments and kinematic analysis of step ascent and descent in adults with Down syndrome

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Abstract

Background Step ascent and descent is one of the most common daily tasks. Although it is generally considered a rather simple movement, it may not be so easy for participants with Down syndrome.
Methods A kinematic analysis of step ascent and descent was conducted, and a comparison between 11 adult participants with Down syndrome and 23 healthy participants was carried out. This analysis was accompanied by a posturographic analysis with the aim of evaluating aspects relating to balance. The principal aim of postural control was to investigate the trajectory of the centre of pressure, while the kinematic analysis of movement included the following: (1) the analysis of anticipatory postural adjustments, (2) the calculation of spatiotemporal parameters and (3) the evaluation of articular range of motion.
Results A general instability for participants with Down syndrome, highlighted in the postural control by an increased anteroposterior and mediolateral excursion, when the test was conducted with both open and closed eyes, was found out. Regarding anticipatory postural adjustments, this deficit in balance control was revealed by the execution of small steps before completing the movement and by a much longer preparation time anticipating the movement. In addition, the kinematic analysis reported a longer ascent and descent time and a lower velocity, accompanied by a greater rising of both limbs in ascent, which indicates an increased perception of the obstacle. Finally, a wider trunk range of motion in both the sagittal and frontal planes was revealed.
Conclusions All the data confirm a compromised balance control that could be associated with damage to the sensorimotor centre.

Keywords APAs, balance control, Down syndrome, kinematic analysis, posturographic analysis, step ascent and descent

Introduction

Step ascent and descent is one of the most common daily tasks. Although it is generally considered a rather simple movement, it may not be so easy for participants characterised by functional limitations and motor disabilities, for example, Down syndrome (DS) (Galli *et al.* 2013; Liang *et al.* 2018). Clinical evidence and literature studies show that the execution of this gesture is particularly difficult also in individuals with cognitive disorders. Even participants with DS are characterised by cognitive impairment that is largely due to an excess of beta-amyloid produced in the brain (Gomez *et al.* 2020). This peptide is processed by the

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beta-amyloid precursor protein, whose gene is located precisely on chromosome 21 (Snyder *et al.* 2020); this seems to be the cause of cognitive decline in this type of population (Holland & Oliver 1995; Fortea *et al.* 2021). Thus, it can be said that cognitive decline is associated, through specific patterns, with the loss of functional activities of daily living (Warren *et al.* 1989; Bassett & Folstein 1991), for example, climbing up and down a step. For this reason, the main purpose of this study was the kinematic analysis of step ascent and descent in participants with DS by means of a comparison between them and a group of healthy individuals.

This analysis was accompanied by a posturographic analysis with the aim of evaluating aspects relating to balance. The principal aim of postural control analysis was to investigate the trajectory of the centre of pressure (CoP). The variation of this coordinate as a function of time is the first parameter of interest in this type of analysis, because from a clinical point of view, it can lead to the identification of alterations in the motor control system related to pathologies of the central nervous and sensory systems. There are numerous articles in the literature that perform this type of analysis in correlation with DS because of the information it provides on the control patterns implemented by the participants (Winter *et al.* 2003; Galli *et al.* 2008a,b, 2014a,b). It has been found that in healthy participants, the CoP excursion in the anteroposterior (AP) direction is greater than the mediolateral (ML) direction, while the opposite occurs for the group with DS; moreover, it was shown that an increase in the ML sway is a good predictor of instability (Maki *et al.* 1994; Galli *et al.* 2008b; Rigoldi *et al.* 2011).

The preparatory actions that are needed to create the postural conditions for a movement are called anticipatory postural adjustments (APAs). These are actions that are controlled by the central nervous system and follow a precise motor pattern. To take a step from a static position, whether to perform a walk or to ascend/descend from a step, the body segments must cooperate synergistically to produce a 'controlled loss of balance'. These movements are very fine and precise strategies that primarily involve the CoP and centre of mass (CoM) and are critical to the proper execution of the desired motor gesture. Rapid postural adjustment to re-establish the loss of balance of the CoM results in a crucial point for fall prevention (Sun *et al.* 2015). Because the onset of ascent and descent from a step is very similar to that of walking, the approach used to study APAs will be similar to that related to gait analysis.

Regarding the motion analysis, reference is made to events reported in literature studies on step ascent and descent (Riener *et al.* 2002; Galli *et al.* 2013). The test involves the participant standing and, at the start signal, climbing up the step (moving his preferred limb first) and stopping once both feet are resting on the step. The descent phase is performed separately and ends once both feet rest on the ground. For both tests, step ascent and descent, the kinematics and the APAs were considered in order to detect specific alterations in preparation phase and consequently to motor control alteration in DS.

Materials and methods

Participants

This multicentre study was conducted by comparing a group with DS and a control group (CG) and was approved by the Ethics Committee of Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS) San Raffaele Pisana in Rome. Functional assessment on the first group was conducted at the Laboratory of Gait Analysis of the IRCCS San Raffaele Pisana in Rome, while the data collection of the second group took place simultaneously in the Laboratory of Posture and Movement Analysis 'Luigi Divieti' of the Politecnico di Milano: the study design is, therefore, observational and analytical. The study involved a group with DS and a CG in order to highlight how DS interferes with motor control during the ascent and descent of a step. In both cases, participants were recruited from the movement analysis laboratory where the tests were then performed; the choice was made from subjects already attending the laboratories according to specific inclusion and exclusion criteria.

Specific selection inclusion criteria were followed for each group. For the control one, these were as follows: (1) the absence of orthopaedic and neurological diseases or disorders, (2) no damage to the somatosensory, auditory and vestibular systems and (3) uncorrectable limitations in visual function. For the group with DS, the inclusion criteria were as follows: (1) diagnosis of trisomy 21 (in the three possible forms) with no congenital heart disease, (2)

normal visual and auditory abilities and (3) independence in walking or maintaining an upright posture. In addition, people who had undergone orthopaedic surgeries, who are currently undergoing major drug treatments or who have had seizure episodes in the past were excluded. A written informed consent form containing all details of the study was signed by all participants involved.

The group with DS selected according to these criteria consisted of 11 participants (4 female and 7 male) with age between 13 and 35 years, while the CG consisted of 23 participants (16 female and 7 male) with age between 20 and 26 years.

Posturographic analysis

The static stabilometric test was performed under two different conditions: with open eyes (OE) and with closed eyes (CE). The participant was asked to stand over the force platform in an orthostatic position: feet slightly apart to form a 30° angle, head and eyes straight ahead and arms extended across the body and slightly open. Once a balanced condition was achieved, a 30-s acquisition was performed. At the end of the test, the same acquisition was repeated by asking the participant to keep his or her eyes closed throughout the test (Galli *et al.* 2008b; Rigoldi *et al.* 2011). The CG was acquired in the 'Luigi Divieti' laboratory with two 60 × 40-cm OPTIMA HPS force platforms (AMTI USA) with a sampling frequency of 500 Hz and equipped with six channels supplied with a 5-V voltage. Instead, at the Rome laboratory, four P-6000 force platforms (BTS Bioengineering) with a sampling frequency of 500 Hz were used to acquire the group with DS.

The values extracted from the posturographic analysis were the length of the CoP trace (sway length) and the AP and ML excursions of the CoP (RoM AP and RoM ML), calculated as the difference between the maximum and minimum values reached by the two components; these are then normalised for the height of the participants (Galli *et al.* 2008b). Next, the coordinates of the midpoint between the markers located on the heel and the fifth metatarsal were calculated for each foot. The point located midway between these two landmarks was considered as a first approximation at the centre of the foot base (cfb). Then the time average of the measured instant-by-instant distance between CoP and cfb, normalised for the participant's height, was evaluated (CoP-cfb) (Rocchi *et al.* 2006). The position of the CoM was assumed to be coincident with that of the marker placed on the sacrum (Rocchi *et al.* 2006).

Step analysis of ascent and descent tasks

The instrumentation used in both laboratories consisted of an optoelectronic system (SMART-DX 400 BTS Bioengineering) operating with passive markers for capturing kinematics with a sampling frequency of 100 Hz. The kinematic model chosen for marker placement was that associated with the Davis anatomical protocol. To simulate ascent and descent stairs, a marked step (Fig. 1a) was placed on one of the force platforms, making sure it was totally positioned inside the platform. The step in both laboratories was chosen with a rise of 16 cm to simulate the steps found in public infrastructure and reproduce, as closely as possible, an everyday life situation (Riener *et al.* 2002). Before performing the actual test, the participant was asked to perform a few ascents and descents to become familiar with the experimental setup (Galli *et al.* 2013) (Fig. 1b,c). The participant was then asked to position himself on the first platform in front of the step. The limb with which to take the first step was left to the total discretion of the participant, it not being the aim of this study to assess differences depending on the climbing limb. When the participant has placed both feet on the step and reached a position of balance, the test was

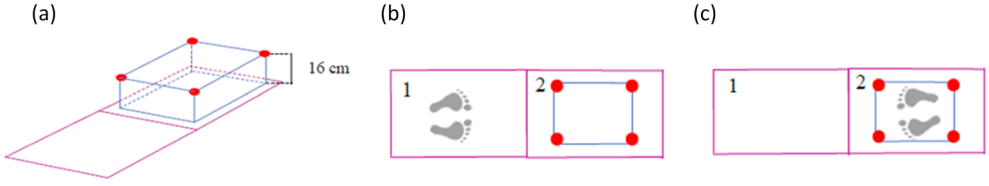

Figure 1. (a) Diagram of the marked (dots) step and its placement on the force platforms. (b) Subject's position for ascent and (c) descent from the step.

considered completed. Each trial was repeated a minimum of three times. The last part of this protocol was the descent from the step, performed with the same instructions as the ascent trial.

The aim of the protocol was to identify two macro-types of parameters: those related to the antecedent phase of ascent and descent, that is, APAs, and those related to the effective movement phase, that is, spatiotemporal parameters and joint excursions.

Ascent and descent from the step

The time parameters evaluated for both the ascent and descent phases are the swing times of the two limbs (t_swing), the double support time (t_ds), the ascent time (t ascent tot) defined as the elapsed time between the detachment of the first foot and the placing of the second foot on the step, and similarly the descent time (t descent tot) evaluated as the time between the detachment of the first foot from the step and the placing of the contralateral foot on the ground. This was followed by the evaluation of the spatial parameters: stride length and stride width defined as the distance in *X* direction (walking direction) and *Z* direction (direction perpendicular to walking direction) between the midpoints of the feet, respectively, and the height attained by foot during the swing phase evaluated as the maximum distance in *Y* direction (vertical direction) between the midpoint of the foot and the step calculated for both the first and second swing limbs. The last spatiotemporal value extrapolated was the velocity of ascent and descent from the step.

For a complete kinematic description, trunk, pelvis, hip, knee and ankle angles were also evaluated.

Anticipatory postural adjustment analysis

For the assessment of APAs, five specific events are distinguished that define the four main stages of APAs (Cau *et al*. 2014; Corsi *et al*. 2019): (1) APAo = initial position of the CoP, before starting to move; (2) APA 1°min = minimum posterior position at the swing limb; (3) APA 1°max = maximum anterior position at the CoP transition from swing limb to stance limb; (4) APA 2°min = minimum posterior position at the stance limb; and (5) End = final position of the CoP.

Thus, the phases identified by these events are as follows: (1) APA1 = defined between the APAo and APA 1°min event and corresponds to the unbalance phase; (2) APA2a = defined between the event APA 1°min and APA 1°max; (3) APA2b = defined between APA 1°max and APA 2°min (this phase together with the previous one represents the unloading phase); and (4) LOC = defined between APA 2°min and End and constitutes the monopodal support phase. The events and subphases are shown in Fig. 2.

The parameters of interest for each of these phases of the CoP trajectory are track lengths, excursions (difference between maximum and minimum coordinate) and velocities. All parameters were evaluated in the AP and ML directions (Delval *et al*. 2012). Then, the vector joining the CoP with the CoM was calculated. This represents a quantity proportional to the acceleration of the CoM (Corsi *et al*. 2019). The calculated parameters previously listed are the same as those illustrated in articles on 'step initiation' (Sun *et al*. 2015; Mizusawa *et al*. 2017) and to those inherent in 'gait initiation' (Cau *et al*. 2014; Sun *et al*. 2015; Corsi *et al*. 2019). In addition, the elapsed time from the start of the CoP movement to the swing of the first foot before performing the ascent or descent from the step was calculated. This parameter represents the time required for the participant to prepare for the actual execution of the motor task (t_prep ascent/descent).

Statistical analysis

All the described parameters were extracted for both the CG and the group with DS, and statistical analysis was performed for both using MINITAB software.

Normality was checked by applying the Kolmogorov–Smirnov test. In case of normal distribution, Student's *t*-test for independent populations was used to compare the averages of the parameters of the two groups; if the data were not found to be normally distributed, the equivalent nonparametric Mann–Whitney *U*-test was applied. For both, the significance level chosen was $P < 0.05$.

For the parameters related to the stabilometric test, in addition to a comparison between the healthy and pathological groups, an analysis was made between OE and CE tests within the same group. For this, Student's *t*-test for paired data and the equivalent nonparametric Wilcoxon signed-rank test were applied, with the significance level of the test always being 0.05.

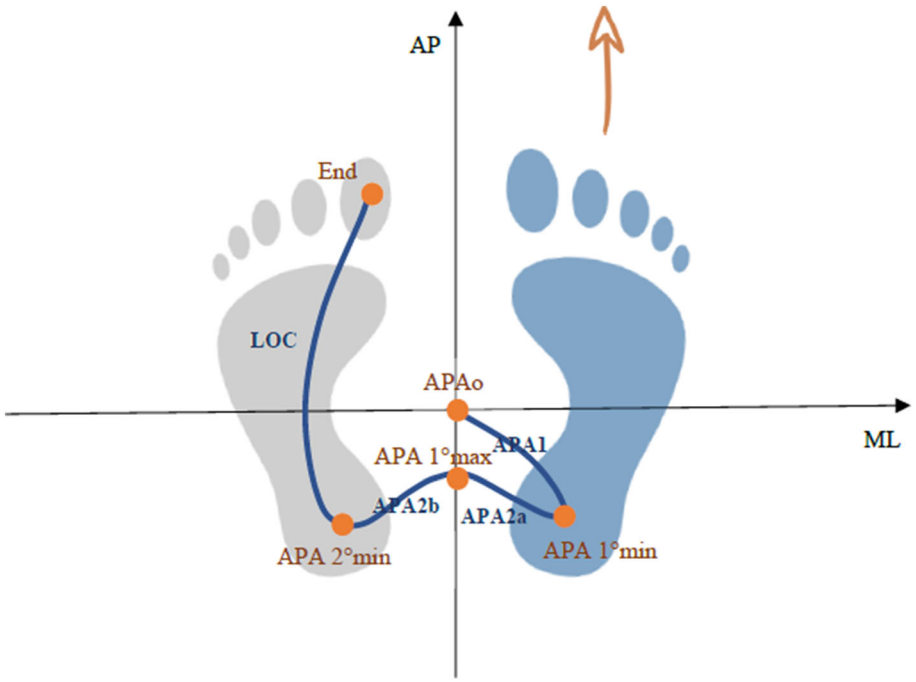

Figure 2. Centre of pressure trajectory during an anticipatory postural adjustment highlighting the main events (dots) and corresponding subphases (lines). The starting foot in this case is the right foot. AP, anteroposterior; ML, mediolateral.

Table 1 Mean (standard deviation) of age, weight, height and BMI of the CG and the group with DS

	Sex	Age	Height (cm)	Weight (kg)	BMI (kg/m^2)
Group with DS	4 F and 7 M	23.18 (5.82)	149.30 (8.16)*	60.92 (10.99)	27.23 (3.89)*
CG	16 F and 7 M	22.83 (1.83)	167.60 (8.70)*	62.09 (9.52)	22.06 (2.53)*

*$P < 0.05$.

BMI, body mass index; CG, control group; DS, Down syndrome; F, female; M, male.

Results

Participants

A preliminary statistical analysis of the anthropometric data, summed up in Table 1, was conducted on the two groups analysed. Normality was first checked by applying the Kolmogorov–Smirnov test. If normal, Student's *t*-test was then used to compare the means; if not, the equivalent nonparametric Mann–Whitney *U*-test was applied. The group with DS had a body mass index (BMI) of 27.23 ± 3.89 kg/m^2, while the CG revealed a lower BMI of 22.06 ± 2.53 kg/m^2.

Note that the average ages of the groups were comparable (*P*-value = 0.956) while the BMI of the group with DS was statistically higher than that of the CG (*P*-value = 0.001). Overweight is a common problem in DS (Jiménez *et al.* 2015; Pino *et al.* 2021); this is not due to a difference with the CG in weight (*P*-value = 0.765) but in height (*P*-value <0.001): in fact, the group with DS had a lower height, which is characteristic of the syndrome (Rubin *et al.* 1998; Bertapelli *et al.* 2016). Considering the small number of participants, it was not considered significant from a statistical point of view to include the evaluations related to the different levels of BMI.

Posturographic analysis

The results for the comparison of CG and group with DS showed a significant difference for all parameters, both with OE and CE; in particular, the values for the group with DS were always higher than for the CG. Table 2 shows the group with DS and CG comparison of the value of the postural sway length, anteroposterior (RoM AP) and ML (RoM ML) excursions and the time-averaged values of the distance between the CoP and the centre of the base of support (CoP-cfb) in the two test modes (OE and CE). In Table 2, data labelled '%height' indicate that the variables were estimated by normalising for the height of the participants.

Interesting results were also observed from the AP and ML coordinate trends of the CoP and CoM, represented on the same graph as a function of the percentage of the total trial duration. An example is shown in Fig. 3 considering the comparison in ML direction of group with DS and CG in condition of OE.

It was obtained that for participants with DS, the deviation between the CoM and CoP curves was much greater than for healthy participants, with both eyes open and closed, while there did not seem to be a clear difference between the two testing modes within the same group. This was then confirmed by the statistical analysis performed within the same group between the OE and CE trials. In fact, no statistically significant differences were found for any parameter except for the CG's postural sway length, which was greater with CE. The values of the averages and their *P*-values are given in Table 3 in which postural data can be observed for both the CG and the group with DS in the two conditions of OE and CE.

Table 2 Mean (standard deviation) of the results of posturographic analysis in OE and CE conditions

	Group with DS	CG	*P*-value
Sway length OE (m)	0.543 (0.113)*	0.179 (0.05)*	1.10×10^{-6}
Sway length CE (m)	0.603 (0.245)*	0.203 (0.05)*	6.37×10^{-4}
CoP-cfb OE (%height)	3.58 (0.949)*	2.40 (0.823)*	3.66×10^{-3}
CoP-cfb CE (%height)	3.50 (0.868)*	2.50 (0.775)*	6.48×10^{-3}
RoM AP OE (%height)	0.640 (0.306)*	1.83 (0.523)*	9.18×10^{-3}
RoM AP CE (%height)	1.79 (0.597)*	1.42 (0.714)*	3.28×10^{-2}
RoM ML OE (%height)	1.53 (0.474)*	0.640 (0.306)*	4.20×10^{-5}
RoM ML CE (%height)	1.21 (0.566)*	0.595 (0.384)*	8.04×10^{-3}

*$P < 0.05$.

AP, anteroposterior; CE, closed eyes; CG, control group; DS, Down syndrome; ML, mediolateral; OE, open eyes.

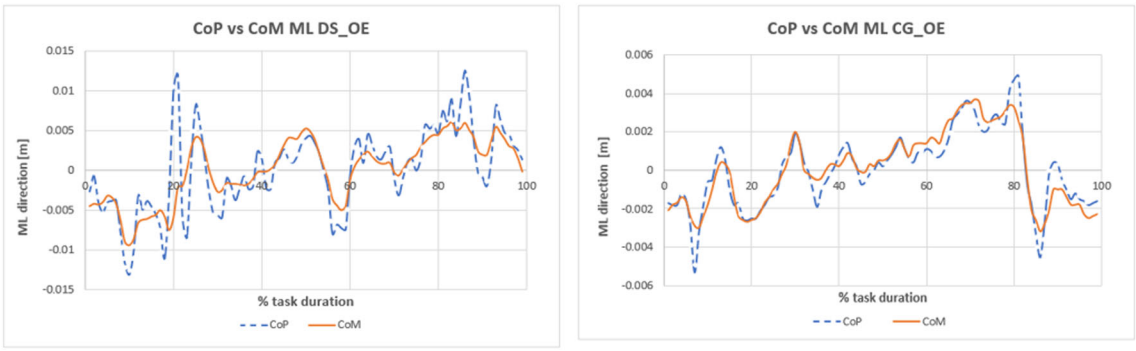

Figure 3. Graph of the mediolateral (ML) coordinate of the centre of pressure (CoP) and centre of mass (CoM) of a healthy subject and a subject with Down syndrome, expressed as a function of task duration for the open-eye test.

Table 3 Mean (standard deviation) of the CG and the group with DS between the OE and CE values of the stabilometric test

		OE	CE	*P*-value
CG	Sway length (m)	0.179 (0.045)*	0.203 (0.05)*	0.032
	CoP-cfb (%height)	2.40 (0.823)	2.50 (0.775)	0.204
	RoM AP (%height)	1.83 (0.523)	1.42 (0.714)	0.495
	RoM ML (%height)	0.640 (0.306)	0.595 (0.384)	0.626
Group with DS	Sway length (m)	0.543 (0.113)	0.603 (0.245)	0.252
	CoP-cfb (%height)	3.58 (0.949)	3.50 (0.868)	0.538
	RoM AP (%height)	0.640 (0.306)	1.79 (0.597)	0.897
	RoM ML (%height)	1.53 (0.474)	1.23 (0.566)	0.185

*$P < 0.05$.

AP, anteroposterior; CE, closed-eye; CG, control group; DS, Down syndrome; ML, mediolateral; OE, open-eye.

Table 4 Mean (standard deviation) of preparation time for CG and group with DS

	Group with DS	CG	*P*-value
t_prep ascent (s)	1.27 (0.855)*	0.585 (0.156)*	2.47×10^{-6}
t_prep descent (s)	1.58 (1.00)*	0.511 (0.177)*	3.10×10^{-14}

*$P < 0.05$.

CG, control group; DS, Down syndrome.

Kinematic analysis

Studying the movement of ascent and descent from the step, first, the results regarding APAs were analysed. From the trajectories of the CoP in the horizontal plane (parallel to the floor) for a participant with DS and a healthy one in the ML and AP directions, it immediately became clear that while for the CG, it was possible to identify all the events that characterise an APA, in the one belonging to the group with DS, this was not possible. This was due to the execution of steps for almost all participants in the group with DS, before performing the ascent or descent. In addition, in some cases, the trajectory appeared to be completely random and not referable to a specific pattern due to foot movements, not even identifiable as steps, performed by the participant. The only one that showed a clean trace comparable with that of the CG was the participant who performed the movement with the support of the physiotherapist, which was therefore not considered. The presence of these attitudes, therefore, did not allow for event selection, and consequently, no APA-related parameters could be compared for the two groups, except for t_prep, as it was defined by the APAo and End events, which were also clearly distinguishable for these traces. In Table 4, the values of t_prep for the CG and the group with DS are shown, and a statistically significant difference is immediately evident during both the ascent and descent from the step. It can be noted that, during both ascent and descent, the difference in t_prep of the group with DS is more than twice that of the CG. The most affected phase appears to be the descent; this is consistent with the insecurity shown by the group with DS in performing movements and the fear of falling described by the participants.

To get a general view of the comparison between the spatiotemporal parameters, a radar chart is shown in Fig. 4 in which the values of the group with DS and those of the CG (green line) are depicted, referred to a reference line corresponding to unity (grey line). The farther the point is from the reference line, the more different are the average values of the two groups. The parameters that show the greatest alterations are t_ds, h_max $_1$ and h_max $_2$, indicating

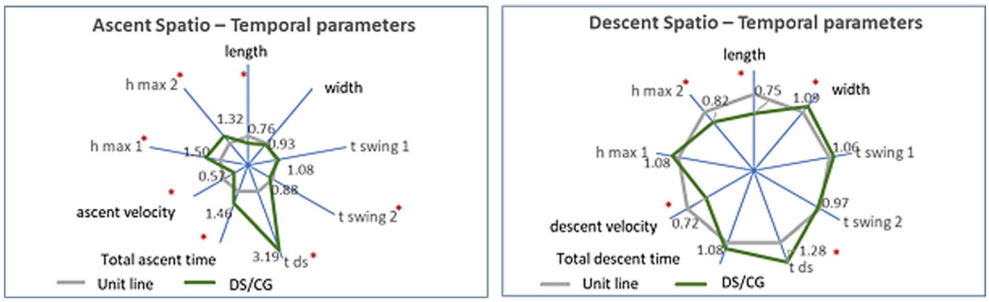

Figure 4. Radar plot of space–time parameters for ascent and descent. The irregular polygon is the ratio of group with Down syndrome (DS) mean values to control group (CG) values, and the regular one is the unit line. $*P < 0.05$.

Table 5 Comparison of spatiotemporal parameters of group with DS and CG group during ascent and descent phases

		Group with DS	CG	*P*-value
Ascent	Step length (m)	0.389 (0.076)*	0.511 (0.028)*	4.16×10^{-10}
	Step width (m)	0.200 (0.033)	0.214 (0.101)	0.316
	t_swing $_1$ (s)	0.731 (0.212)	0.678 (0.155)	0.171
	t_swing $_2$ (s)	0.471 (0.096)*	0.536 (0.076)*	1.03×10^{-3}
	t_ds (s)	1.05 (0.742)*	0.328 (0.128)*	1.15×10^{-11}
	t ascent tot (s)	2.22 (0.794)*	1.53 (0.285)*	2.70×10^{-8}
	Ascent velocity (m/s)	0.201 (0.078)*	0.355 (0.057)*	9.79×10^{-6}
	h_max $_1$ (m)	0.152 (0.038)*	0.101 (0.029)*	2.14×10^{-8}
	h_max $_2$ (m)	0.173 (0.041)*	0.131 (0.023)*	2.04×10^{-6}
Descent	Step length (m)	0.367 (0.070)*	0.493 (0.077)*	1.21×10^{-13}
	Step width (m)	0.191 (0.034)*	0.175 (0.029)*	1.63×10^{-3}
	t_swing $_1$ (s)	0.682 (0.115)	0.644 (0.085)	0.167
	t_swing $_2$ (s)	0.472 (0.114)	0.487 (0.055)	0.066
	t_ds (s)	0.193 (0.086)*	0.151 (0.041)*	2.46×10^{-3}
	t descent tot (s)	1.38 (0.296)	1.28 (0.147)	0.194
	Descent velocity (m/s)	0.301 (0.080)*	0.420 (0.061)*	4.76×10^{-11}
	h_max $_1$ (m)	0.110 (0.022)	0.102 (0.027)	0.069
	h_max $_2$ (m)	0.147 (0.036)*	0.179 (0.039)*	3.65×10^{-5}

Subscripts 1 and 2 refer to the first and second limbs.

$^*P < 0.05$.

CG, control group; DS, Down syndrome.

an insecurity during the single-support phase and altered perception of the obstacle and by the participants in the group with DS. All numerical values, corresponding to the data shown in Fig. 4, have been also summarised in Table 5 in which all statistically significant differences between the CG and the group with DS in both the ascent (step length, t_swing $_2$, t_ds, t ascent tot, ascent velocity, h_max $_1$ and h_max $_2$) and descent (step length, step width, t_ds, descent velocity and h_max $_2$) phases are reported. Please refer to the Discussion section for an in-depth explanation of the results.

Regarding joint angles, RoMs were calculated for the frontal, sagittal and horizontal planes of the hip, knee, ankle, pelvis and trunk. The main results are presented in Table 6. Even in this case, there was a big difference between the CG and the group with DS with statistically significant differences in both the ascent (F/E knee $_1$, F/E knee $_2$, D/P ankle $_1$, F/E hip $_2$, OBL trunk, TILT trunk and TILT pelvis) and descent (F/E knee $_1$, F/E knee $_2$, D/P ankle $_1$, F/E hip $_1$, F/E hip $_2$, OBL trunk, TILT trunk and TILT pelvis) from the step. Such a pronounced difference in the joint angles and RoMs indicates two very

Table 6 Comparison of RoM of group with DS and CG group during ascent and descent phases

		Group with DS	CG	*P*-value
Ascent	F/E knee $_1$ (°)	77.1 (13.4)*	71.7 (10.8)*	0.028
	F/E knee $_2$ (°)	68.4 (10.0)*	55.8 (9.01)*	9.98×10^{-8}
	D/P ankle $_1$ (°)	36.0 (16.7)*	22.0 (6.56)*	6.00×10^{-9}
	D/P ankle $_2$ (°)	43.5 (13.1)	40.0 (8.09)	0.108
	F/E hip $_1$ (°)	51.9 (7.43)	50.3 (6.04)	0.261
	F/E hip $_2$ (°)	42.7 (9.24)*	34.2 (6.24)*	2.47×10^{-5}
	OBL trunk (°)	11.1 (7.97)*	5.08 (2.77)*	7.00×10^{-9}
	TILT trunk (°)	16.6 (9.49)*	11.1 (4.05)*	7.10×10^{-4}
	TILT pelvis (°)	13.5 (3.84)*	8.71 (3.01)*	5.10×10^{-9}
Descent	F/E knee $_1$ (°)	49.4 (17.72)*	54.3 (11.1)*	0.019
	F/E knee $_2$ (°)	77.1 (11.0)*	83.1 (14.1)*	9.96×10^{-5}
	D/P ankle $_1$ (°)	57.5 (14.3)*	45.1 (7.04)*	3.59×10^{-5}
	D/P ankle $_2$ (°)	35.4 (6.21)	34.8 (10.3)	0.697
	F/E hip $_1$ (°)	41.2 (6.35)*	48.5 (6.49)*	9.90×10^{-7}
	F/E hip $_2$ (°)	29.5 (10.2)*	38.7 (7.34)*	3.37×10^{-5}
	OBL trunk (°)	8.01 (4.67)*	3.72 (1.69)*	6.49×10^{-9}
	TILT trunk (°)	16.2 (10.3)*	9.55 (6.06)*	8.30×10^{-6}
	TILT pelvis (°)	8.28 (3.19)*	5.77 (1.90)*	1.71×10^{-4}

Subscripts 1 and 2 refer to the first and second limbs.
*$P < 0.05$.
CG, control group; D/P, dorsiflexion/plantarflexion; DS, Down syndrome; F/E, flexion/extension; OBL, obliquity.

different movement strategies between healthy participants and participants with DS in dealing with the same exercise.

Discussion

Posturographic analysis

Kinematic analysis conducted on the step ascent and descent of participants with DS showed a certain degree of insecurity and instability, which can also be attributed to a general lack of balance that characterises people with this disorder. The latter statement not only finds confirmation in previous literature papers but is also supported by the results obtained in this study regarding posturographic analysis conducted with both eyes open and eyes closed. The comparison between the two groups showed not only a higher AP RoM in the group with DS but also a much larger ML excursion in the CG, in agreement with the literature (Galli *et al.* 2008b). This was considered an index of instability for the group with DS (Maki *et al.* 1994). In agreement with a wider excursion in both directions, the trace length of the CoP for the group with DS was found to be much wider with both OE and CE. In addition, a greater mean distance of the CoP from the centre of the base of support compared with the CG indicates that the postural sway covers a much larger area, and consequently, the oscillatory movement of these participants was much more pronounced, reconfirming impaired balance control. These findings are perfectly consistent with the pathologies of the motor system of these participants, who are in fact characterised by ligamentous laxity and significant hypotonia; this may also have repercussions on the maintenance of upright posture (Galli *et al.* 2008b; Rigoldi *et al.* 2011).

The OE–CE intergroup comparison showed no particular differences for the CG: this is an indication that the proprioceptive system is working properly to compensate for the lack of information from vision. No differences were also found for the group with DS. This could lead to the same conclusion illustrated for the CG; however, this would be in disagreement with the results obtained from the comparison between the two groups. This can be explained using the biomechanical inverse pendulum model

(Winter *et al*. 2003). The group with DS has a higher BMI than the CG because of the lower height; this means that it is possible to schematise the group with DS with a pendulum having the mass placed at a lower height (thus shorter pendulum length). This means that for the same angular increment with respect to vertical position between a participant with DS and a healthy one, the first one would obtain a smaller AP or ML excursion. The results obtained, therefore, between the OE and CE comparison of this category can be explained more by biomechanical rather than cognitive/motor considerations.

Kinematic analysis

Anticipatory postural adjustments

The analysis regarding the APAs of step ascent and step descent of group with DS reported traces that were not comparable with those of CG. This basically was because the movements being compared were not the same: while the CG did an ascent and descent from step from a standing position as instructed by the operator, the group with DS had to perform a few steps in preparation for the task. The need to perform these movements is, therefore, the most evident result of the fact that the group with DS shows some degree of difficulty in ascending and descending steps, although this did not make it possible to obtain most of the numerical parameters for the comparison between the two groups. These considerations are even more interesting in relation to the participant who was given help during ascent and descent, the only one that performed the movement correctly and had a track comparable with that of the CG. This is a clear indication of the insecurity felt by group with DS when facing the exercise alone. The only parameter that could be used to describe the phenomenon was t_prep, which describes the time taken from when the movement is decided (first instant when the CoP moves) to the instant when it is actually performed (detachment of the toe of the first swing limb to make the ascent or descent). The fact that the group with DS had to perform small preparatory movements was the main reason why the t_prep of this category turns out to be much higher – more than twice in ascent and up to more than three times in descent – than that of the CG. Although this parameter cannot provide information about the subphases of this preparatory movement, it appears to be a reliable index and highly indicative of the difficulty exhibited by the group with DS, which results to be greater on the descent than on the ascent.

Ascent and descent from the step

Regarding spatiotemporal parameters, a lower velocity in movement execution was obtained for participants with DS resulting in a longer duration, as reported in the literature (Galli *et al*. 2013). This is indicative of a lack of coordination and lower muscle tone, characteristic of DS. In the specifics of ascent, a t_ds of more than three times that of the CG accompanied by a lower t_swing $_2$ was obtained for the group with DS. This causes almost half of the entire ascent movement to be in double support, while in the CG, it is about one-third of the total movement time. This agrees with a general instability attitude of the group with DS that prefers double support and tries to shorten the swing time in which the participant is in monopodal support, especially of the second swing limb in which the CoM raise and move forward. Indeed, this movement is more complex to coordinate in the presence of reduced lower limb muscle tone. The same motivation could explain the shorter stride length, but this could also be caused by lower group with DS height.

Another important result is a higher maximum height reached by both feet, especially for the first swing limb, for DS participants. This would lead to assume that the group with DS has a higher perception of the obstacle than the CG (Cowie *et al*. 2012), also explaining why they take steps before performing the motor task. In descent, on the other hand, this difference on height is not found for the first swing limb but only for the second. Also, in this case, the stride length is reduced, the descent time is longer, and, thus, a lower descent velocity is obtained than in CG. Furthermore, also in descent, there is a general instability attitude, which results in a higher step width to have a wider support base.

Regarding joint angles, the most significant differences were obtained at the level of both knees, the ankle of the first swing limb and finally the trunk (Galli *et al*. 2013). In particular, in ascent, the RoM of flexion–extension of the knees of group with DS was higher because of a hyperextension in the swing phase of both limbs, which, together with a higher maximum height reached by both feet, would confirm

the hypothesis of an altered perception of the obstacle. In descent, on the other hand, the difference was due to decreased RoM in group with DS, possibly attributable to a lower muscle tone. Regarding the joint excursion of the ankle of the first swing limb of the group with DS, it was greater in both ascent and descent. In the ascent phase, it would seem to be due to enhanced dorsiflexion, and in the descent phase, on the other hand, it was due to hyperplantarflexion, which could explain a motor strategy also present in these participants in walking, which leads them to prefer a tiptoe stance (Parker *et al*. 1986). Another explanation could be weakness at the level of the tibialis anterior. RoM related to obliquity (frontal plane) and tilt (sagittal plane) of the trunk was also shown to be greater in both ascent and descent in the group with DS. This again shows a difficulty for these participants in maintaining good balance control in both planes, and this would reflect damage to sensorimotor centres common in these participants (Roizen & Patterson 2003).

Conclusion

In this study, analysis of the posturography and step ascent and descent of participants with DS was considered and compared with that of healthy participants. The objective was to conduct a kinematic analysis to quantify the motor impairment that these participants exhibit at the level of balance and specifically in performing a motor task such as step ascent and descent. The results showed in general some difficulty in performing this motor task attributable to a lack of balance that was manifested in stabilometric tests with much larger AP and especially ML excursions than in healthy participants. This is due to both ligamentous laxity and muscle hypotonia but may also be indicative of impaired motor patterns for stability. The APAs of these participants are characterised by the presence of small steps that show insecurity and greatly lengthen the time they need to prepare for the ascent and descent movement. This insecurity could also be due to a distorted perception of the step that would lead them to perceive it as a higher obstacle, which would also explain a higher maximum height reached by both feet in ascent than in the CG. In general, the lack of stability characterising participants with DS is also evidenced in a lower velocity in the execution of the task in both directions, favouring the double-stance phase. As further evidence of this, a greater stride width on descent is indicative of the search for a wider and therefore more stable base of support, and finally, a more pronounced trunk sway in both the frontal and sagittal planes not only evidences a more precarious balance but could also reflect damage to the sensorimotor centres of individuals with trisomy 21.

An important implication that can be deduced is that the analysis conducted between the CG and the group with DS revealed substantial differences in the motor pattern. Participants with DS showed greater difficulty in movement execution and reduced balance; with the information extrapolated from this study, it is possible to go in for much more targeted rehabilitative treatments that will allow for improved quality of life.

A few limitations of this study were found, the first of which concerns the limited size of the sample; it would be interesting to repeat the analysis on a larger sample. A second limitation concerns the impossibility of comparing the parameters relating to APAs between the CG and the group with DS; in the future, it could be thought of carrying out an electromyography analysis in order to see the muscular activation of these participants during the initiation of movement. Lastly, it would be interesting to have data regarding the level of cognitive impairment in order to assess a possible correlation between altered motor control and the participant's cognitive level.

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Conflict of interest

The authors declare no conflicts of interest.

Ethics statement

Informed consent was obtained from all subjects involved in the study. The approval of the study was

carried out by the ethics committee with protocol number DOPLAGA-19/35-12/2019.

Author contributions

Cristina Ferrario: Data curation; formal analysis; writing – original draft. **Claudia Condoluci:** Clinical assessment of the participants; review and editing. **Marco Tarabini:** Review and editing; supervision. **Carlotta Maria Manzia:** Clinical assessment of the participants. **Manuela Galli:** Conceptualization; review; editing and supervision. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available because of privacy or ethical restrictions.

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