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Review Article

Gait and postural control patterns and rehabilitation in Down syndrome: a systematic review

Matteo Zago, PhD[1)*], Natalia Almeida Carvalho Duarte, RPT, PhD[1, 2)], Luanda André Collange Grecco, RPT[3)], Claudia Condoluci, MD[4)], Claudia Santos Oliveira, RPT, PhD[5)], Manuela Galli, PhD[1)]

[1)] *Department of Electronics, Information and Bioengineering, Politecnico di Milano: Via Golgi 39, 20133, Milano, Italy*
[2)] *Santa Casa de Misericordia de Presidente Prudente, Brazil*
[3)] *Center of Pediatric Neurostimulation, CENEPE Rehabilitation, Brazil*
[4)] *IRCCS San Raffaele Pisana, Italy*
[5)] *University Center of Anápolis, Uni Evangélica, Brazil*

Abstract. [Purpose] To describe (1) the current knowledge on gait and postural control in individuals with Down syndrome in terms of spatiotemporal, kinematics and kinetics, and (2) relevant rehabilitation strategies. [Methods] Randomized and non-randomized clinical trials published between January 1997 and October 2019 were selected by searching four scientific databases. We included studies on patients with Down syndrome involving gait analysis or postural control. A custom data-extraction and appraisal form was developed to collect the key features of each article. The PEDro Scale was used to evaluate the methodological quality of the studies. [Results] A total of 37 out of 146 cross-sectional and longitudinal studies were included in the review. The main abnormalities included: reduction of gait velocity and step length, poor static balance with increased anteroposterior and mediolateral oscillations and a larger step width. [Conclusion] A number of compensatory patterns during movement was observed, with a direct influence on improvements in stability and postural control throughout daily life. Intensive gait training at an early age appears to produce long-term improvements in this population. Future research should focus on the interaction between the motor and cognitive function, and on the functional effects due to the exposure to an enriched environment.

Key words: Neurological disorders, Gait, Rehabilitation

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INTRODUCTION

Down syndrome (DS) has been widely studied in the field of physical rehabilitation with the aim of identifying the relationship between motor characteristics and the impairment of functional performance[1–7)]. The main features of DS are delayed neuropsychomotor development, global muscle hypotonia and ligament laxity, that result in an average of two years for gait acquisition[8)] and in compromised cognitive functions[6, 9, 10)]. Motor abnormalities often lead to the development of abnormal postural control, resulting in instability and an impaired gait pattern, with an increased energy expenditure and reduced performance[11–13)].

*Corresponding author. Matteo Zago (E-mail: matteo2.zago@polimi.it)
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Postural control training was reported to facilitate the motor function and to exert a considerable influence on gait patterns[6, 8, 14, 15]. The reduced velocity and quality of postural reactions in DS produce compensatory movement patterns during the phases of the gait cycle. Affected individuals develop inappropriate patterns in an attempt to establish functional, relatively stable gait. Altered gait patterns are related to orthopedic changes that in turn have negative consequences on performance during the execution of different daily-life activities[1, 11, 16, 17].

Comprehensive knowledge on postural control, kinematics, kinetics and spatiotemporal variables during the phases of the gait cycle is required for the establishment of an effective therapeutic protocol for individuals with DS. The analysis of gait and balance allows to objectively identify altered biomechanics patterns compared to healthy individuals, enhancing the design of therapeutic pathways[1, 17, 18]. However, there is an increasing need of standardization concerning the definition of abnormalities in gait and postural control in individuals with DS. This would facilitate the design of therapeutic interventions at different stages of life. To the best of our knowledge, no Systematic Review has ever summarized this topic; thus, the aim of the present work is two-fold: (1) to identify the main features regarding gait and postural control in individuals with DS, in terms of kinematic, kinetic and spatiotemporal variables; (2) to describe the main intervention strategies adopted for rehabilitation.

METHODS

A systematic literature review was performed between February 1st and September 30th, 2019, searching for studies involving the evaluation of gait analysis and postural control in individuals with DS. Searches were performed in the EMBASE, PubMed, Web of Science and MEDLINE databases using a combination of the following keywords: “Down syndrome”, “gait analysis”, “gait pattern” and “postural control”. The logical operators “and” / “or” were used in each combination. In addition, the references of the retrieved studies were analyzed to identify further potentially relevant publications.

The PRISMA (Preferential Report Items for Systematic Analysis and Meta-Analysis) guidelines[19] were followed in assessing literature results. During the study selection process, two independent researchers blindly analyzed titles and abstracts. When the title and abstract did not contain sufficient information to decide for the eligibility, the two researchers scrutinized the full text. In cases of divergence, a third researcher was asked to perform the analysis.

The following inclusion criteria were considered: (i) longitudinal and cross-sectional studies published in English; (ii) papers assessing patients diagnosed with Down syndrome; (iii) studies involving all ages; (iv) studies involving postural control analysis or (v) studies involving gait analysis (kinematics and/or kinetics); (vi) studies published in the last 20 years. Articles were not included if they fell into the following exclusion criteria: (i) single case reports; (ii) neuroscience studies involving gait with dual tasks; (iii) studies analyzing the upper limb function; (iv) studies evaluating the effects of associated comorbidities on the gait pattern; (v) studies whose PEDro (Physiotherapy Evidence Database) score was lower than 5 points[20].

The PEDro Scale, returning a score from 1 to 11, was used to evaluate the methodological quality of the studies[20]. The higher the score, the higher the study quality: we included papers with moderate to high quality, i.e. those scoring 5 points or higher.

A custom data extraction and appraisal form was used to collect the key features of each paper: (1) meta-data (authorship, publication year); (2) demographics (sample size, age); (3) clinical and functional characteristics; (4) assessment tools; (5) gait analysis and postural control—parameters and results; (6) outcomes of gait analysis and postural control tests; and (7) whether the study involved behavioral interventions, the objectives and parameters of the intervention, the results of the intervention and its relationship with neurophysiological findings. After reviewing the results of the selected studies, it was decided that a meta-analysis was not appropriate because the intervention protocols and the outcome measures significantly varied across the studies.

RESULTS

A total of 146 articles were initially retrieved. After titles screening, 59 studies were retained for further inspection. Following full-text analysis, 37 studies were included in the review (Fig. 1). Of them, twenty-six (70%) focused on gait analysis[1, 2, 5, 11–13, 17, 21–37] while 11 (31%) studies evaluated postural control during standing[14, 15, 38–45]. Overall, a total of 1,299 subjects with DS were considered. The number of participants per study ranged from six to 230; the age of the participants ranged from 6 months to 50 years.

The average PEDro score was 6.1—details are available as Supplementary Table. Just five papers reported random and concealed allocation. All studies reported measures of variability and intention to treat analysis; more than 85% reported follow-up and intra-group analysis. The therapists were not blind in any study, while two of the studies reported blinding of the participants[14, 35].

The main abnormalities regarding spatiotemporal gait variables among children, adolescents and adults with DS compared to age-matched typically developing controls were: reduced gait velocity, reduced step length[2, 12, 23, 25, 34], and an increase in step width[46]. In general, individuals with DS walk with greater hip flexion throughout the entire gait cycle, greater knee flexion during the stance phase and limited range of motion regarding plantar flexion of the ankle at initial contact[2, 11, 36].

On the postural control side, greater body sway in the mediolateral and anteroposterior directions were found with respect to age-matched healthy individuals[40, 42, 44, 47].

The studies assessing spatiotemporal parameters involved individuals aged from 6 months to 50 years. Table 1 lists patients' demographics and the main outcomes of the studies included. Two studies showed that in early childhood, spatio-temporal variables in children with DS have similar values as controls[2, 46]. After gait maturation, the main differences among the children with respect to controls were: reduced step length (a drop of about 10 cm with respect to typical developing individuals) and significantly slower gait velocity, which was reduced of about 0.4 m/sec[11]. Throughout life, however, individuals with DS showed improvements in step length, alongside with a reduced support base and consequent reduction in step width[2]. Horvat et al.[25, 48] showed that people with DS exhibit lower performance than healthy counterparts in terms of step length, step width, stride length, in the preferred walk condition, in the fast walk condition and during dual task conditions. Consistently, Salami et al. found that young adults with DS had reduced gait velocity and step length, while energy recovery had no differences from healthy people to people with Down syndrome[13]. These features also apply to gait involving stepping over obstacles.

The main kinematic abnormalities were an increase in knee flexion during the mid-stance phase and a reduction in knee flexion during the swing phase as well as a reduction in peak plantar flexion at toe-off (Table 2). Moreover, a reduction in ankle range of motion was found, with a lower peak dorsiflexor activity at the beginning of the stance phase[11].

More specifically, Rigoldi et al. revealed an excessive anterior pelvic tilt, reduced hip flexion by about 10–15 degrees in the stance phase, reduced knee flexion in the swing phase (drop of up to 15 degrees) and lower average knee flexion-extension values throughout the entire gait cycle[22]. Analogous differences in the kinematic pattern were found in studies comparing individuals with DS to healthy controls[2, 27], the latter highlighting a significant reduction in ankle range of motion in DS, with a wider plantar-flexion range observed during the entire movement. Recently, two studies[32, 33] evaluated the differences in gait kinematic parameters between men and women with Down Syndrome in more than 340 patients aged 7–50 years. Overall, the gait function in females seems to be more impaired than in males, with the exception of foot progression. Women with DS exhibit a larger hip flexion at late stance (42% to 54% of the gait cycle) and reduced knee flexion at the beginning of the swing phase (61% to 69% of the gait cycle), step length was shorter, and the Gait Profile Score (GPS, a synthetic measure of gait abnormality) was higher than in male patients[32, 33].

Two additional other studies[17, 26] found that DS group showed more marked and speed-dependent responses to perturbations than in healthy controls, and that the coordination patterns in children with DS were less stable, especially in the medio-lateral direction—this was evidenced by a larger center of mass mediolateral displacement. The authors related these findings to a higher level of instability and energy expenditure (in particular, net metabolic rate) in individuals with DS[12].

Twelve of the included studies studied kinetic variables (Table 3). According to Wu et al., children with DS increase the vertical propulsive impulse, facilitating the initiation of leg swing[23]. In addition, individuals with DS display limited ankle movement during the initial stance and pre-swing phases, which was related to low propulsion and push-off capability[40]. The center of pressure (CoP) in patients with DS is anteriorly positioned with respect to the ankle, resulting in an anticipated ankle plantar flexion, likely due to the reduction in force and to a flat feet condition[50], suggesting muscle weakness compromising the gait function. Similarly, Rigoldi et al. also observed a larger displacement of the CoP in the mediolateral direction, and reduced CoP displacement in the anteroposterior direction during the stance phase[42].

More specifically, individuals with DS tend to have greater hip and ankle stiffness in comparison to healthy controls[1, 25].

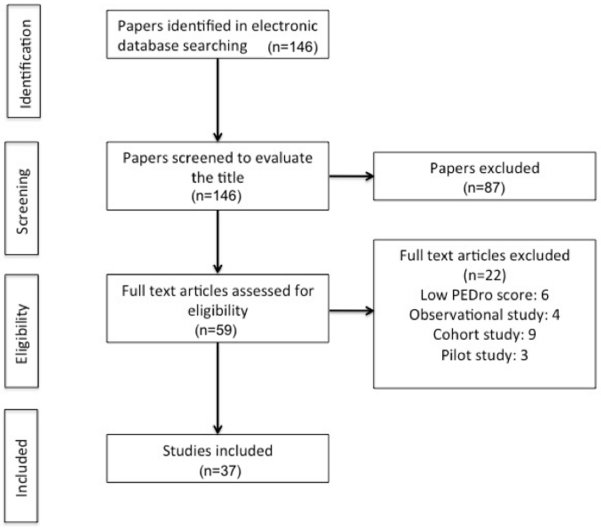

Fig. 1. Flowchart of the systematic review process, according to the PRISMA statement.

Table 1. Spatiotemporal gait parameters of the studies included in the review

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Kubo et al., 2006[26]	DS: 8 (8–10 years) CG: 8 (8–10 years)	Comparison of spatiotemporal parameters at the onset of walking, and one month after the acquisition of independent gait.	None.	Slower gait velocity; shorter stride length; greater stride frequency.
Looper et al., 2006[37]	CG: 9 (6–8 months) DS: 6 (6–8 months)	Gait evaluation at 1, 3, 4, 6 and 8 months of walking experience.	Treadmill training: 2 months after onset of walking, 3, 6 and 12 months. Low- and high-intensity treadmill training.	DS group, onset of walking: variability in step length greater than in step width. With practice, reduction in step length variability, but increase in step width.
Galli et al., 2008[11]	CG: 30 (5–13 years) DS: 98 (6–15 years)	Comparison of kinematic and kinetic variables between groups.	None.	Reduced gait velocity and step length.
Wu et al., 2008[24]	DS: 30 (10 months)	How newly walking toddlers adopted clearance strategies and modified anticipatory locomotor adjustments patterns to negotiate an obstacle.	"Low intensity-generalized" training, or "high intensity-individualized" training.	Both groups (low- or high-intensity training) reduced velocity, cadence and step length, and increased step width during the last three pre-obstacle steps.
Agiovlasitis et al., 2009[17]	DS: 15 (19–44 years) CG: 15 (18–42 years)	Gait analysis before and after each session.	Treadmill training at different speed for 2–4 weeks.	Greater variability in step width and length, reduction in step duration.
Rigoldi et al., 2009[36]	DS: 9 CG: 10 Children (age not available)	Associate cerebral volumes with walking characteristics.	None.	Less functional gait associated with smaller cerebellar vermis volume.
Cimolin et al., 2010[1]	DS: 21 (18–39 years) PW: 19 (17–40 years) CG: 20 (24–42 years)	Comparison of kinematic and kinetic variables between groups.	None.	Reduced stance phase, step length and velocity of progression.
Rigoldi et al., 2011[42]	DS groups: 10 children (9.2 years), 15 adolescents (16.7 years), 16 adults (37.3 years); CG (mean age: 8.1, 18.0 and 37.6 years, respectively)	Comparison of spatiotemporal parameters and joint angles among groups.	None.	In children: shorter step length; increase in step length throughout life.
Horvat et al., 2012[5]	CG: 12 (18–28 years) DS: 12 (18–28 years)	Comparison of spatial and temporal gait parameters.	Responses to preferred and fast walking speed.	Significant group differences for step length, step width, stride length, and velocity in the preferred walk condition.
Rigoldi et al., 2012[22]	DS: 16 (31–45 years) ED: 12 (36–59 years) CG: 20 (30–50 years)	Comparison of kinematic and kinetic variables between groups.	None.	Slower gait velocity in comparison to other groups; shorter step length and stance phase duration.
Horvat et al., 2013[25]	CG: 12 (22.5 years) DS: 12 (22.8 years)	Comparison of spatial and temporal movements between groups.	Response to dual task condition.	Movements are less efficient and functional in individuals with DS when an additional task is encountered while walking.
Galli et al., 2014[35]	DS: 29 (9.8 years) CG: 15 (9.2 years)	Comparison of kinematic and kinetic variables.	Association between flat feet and gait pattern.	Lower peak ankle plantar flexion moment and maximum ankle power during terminal stance.
Salami et al., 2014[13]	39 adults DS: 21 (18–29 years) CG: 18 (21–30 years)	Comparison of spatiotemporal and kinetic parameters between groups, walking with and without obstacles.	None.	Lower velocity; lower and more variable length; greater step width.
Wu et al., 2014[23]	DS: 10 (9.12 years) CG: 10 (9.31 years)	Comparison of spatiotemporal parameters.	None.	Self-selected speed: slower walking velocity and shorter stride length in DS group than in typically developing toddlers.

Table 1. Continued

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Belluscio et al., 2019[34]	DS: 15 (6.63 years) CG: 12 (6.10 years)	Comparison of spatiotemporal parameters and indices related to stability obtained from inertial sensors.	None.	Children with DS exhibited reduced gait symmetry and higher accelerations at pelvis level than CG. Stride length significantly reduced in DS.

Age is expressed as range or mean, according to availability.
AP: anteroposterior; COP: center of pressure; COG: center of gravity; CG: control group; DS: Down syndrome; ED: Ehlers-Danlos. ML: mediolateral; ROM: Range of motion.

Table 2. Kinematic gait parameters of the studies included in the review

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Kubo et al., 2006[26]	CG: 10 (8–10 years) DS: 12 (8–10 years)	Assessing pelvis and HAT movements and their coordination during treadmill walking in the AP and ML directions.	Walking on a treadmill at 40%, 75% and 110% of preferred walking speed.	Coordination patterns in DS were less stable, especially in medio-lateral direction at slow speed.
Galli et al., 2008[11]	CG: 30 (5–13 years) DS: 98 (6–15 years)	Comparison of kinematic and kinetics variables between groups.	None.	Greater hip flexion during gait. Knee: greater flexion in stance phase, less flexion in swing phase, less range of motion. Ankle: greater plantar flexion at initial contact and less plantar flexion at toe-off.
Rigoldi et al., 2009[36]	DS: 9 CG: 10 Children (age not available)	Associate cerebral volumes with walking characteristics.	None.	Greater hip flexion throughout gait cycle; greater knee flexion in stance phase; decreased ROM dorsiflexion/plantar flexion and extra-rotated foot progression More flexed hip and worse knee joint condition.
Cimolin et al., 2010[1]	DS: 21 (18–39 years) PW: 19 (17–40 years) CG: 20 (33.4 years)	Comparison of kinematic and kinetics variables between groups.	None.	Reduced knee and hip flexion at initial contact. Forward-tilted pelvis on sagittal plane. Excessive hip flexion throughout gait cycle. Ankle: plantar-flexed during stance phase with reduced range of motion.
Galli et al., 2010[27]	CG: 11 (Mean age: 20.2 years) DS: 15 (Mean age: 19.6 years)	Quantifying functional limitations.	None.	Longer durations in execution across all tasks in the DS group. Significant difference in ankle ROM during leg-lifting, with a wide plantar-flexion demonstrated during the entire movement.
Wu et al., 2010[21]	DS: 30 (infants)	Evaluate treadmill training.	Low- and high-intensity treadmill training until walking onset.	High-intensity group: peak ankle plantar flexion at or before toe-off; Low-intensity group: peak ankle plantar flexion after toe-off.
Rigoldi et al., 2011[2]	DS groups: 10 children (9.2 years), 15 adolescents (16.7 years), 16 adults (37.3 years); CG (mean age: 8.1, 18.0 and 37.6 years, respectively)	Comparison of kinematic and kinetics variables between groups.	None.	DS: Greater hip flexion throughout gait cycle; Greater hip abduction and adduction; Reduced ankle ROM in teenagers and adults compared to CG.
Rigoldi et al., 2012[22]	DS: 16 (31–45 years) ED: 12 (36–59 years) CG: 20 (30–50 years)	Comparison of kinematic and kinetics variables between groups.	None.	Greater forward tilt and flexion of pelvis in swing phase; higher hip flexion throughout gait cycle and less hip flexion in stance phase. Knee: lower peak flexion and range of motion (flexion-extension) during gait. Ankle: lower peak plantar flexion at end of stance phase and range of motion during gait.

Table 2. Continued

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Wu et al., 2014[23]	DS: 10 (9.12 years) CG: 10 (9.31 years)	To investigate the effect of both walking speed and external ankle load on the kinematic patterns of treadmill walking.	Treadmill speeds were set at 75% and 100% of the preferred walking speed.	Both groups showed similar kinematic values.
Agiovlasitis et al., 2015[12]	CG: 15 (28 ± 6 years) DS: 15 (27 ± 8 years)	To examine the extent to which gait characteristics explain differences in net-MR during walking.	Participants walked at six, randomly selected, walking speeds.	Step length variability made the greatest unique contribution (10.6%) to the higher net-MR in adults with DS, followed by the range of COM mediolateral motion (6.3%), step width variability (2.8%), and variability in COM anteroposterior velocity (0.7%).
Chen et al., 2016[28]	CG: 15 (7–9 years) DS: 15 (7–9 years)	Compare kinematic features between groups.	Walk and cross obstacles with heights of 10%, 20% and 30% of the leg length.	Children with DS tend to adopt a lower speed and larger step width when they perceive instability. They adopt a pelvic strategy (i.e., greater pelvic leading-side listing and forward rotation) to achieve a higher leading toe clearance with a longer step length.
Pau et al., 2019[32]	DS: 117 Females: 53 (26.7 years); Males: 64 (27.8 years)	To assess kinematic differences between men and women with DS.	None.	Women: larger hip flexion at late stance and reduced knee flexion at the beginning of the swing phase. Men: larger foot external rotation through most of the stance phase and at the end of the swing phase.
Zago et al., 2019[33]	DS: 230 (7–50 years). Females: 103, Males 127	To assess kinematic differences between men and women with DS.	None.	Shorted step length and higher Gait Profile Score in females.

Age is expressed as range or mean, according to availability.
AP: anteroposterior; CG: control group; DS: Down syndrome; HAT (head, arms and trunk); ML: mediolateral.

Table 3. Kinetic features of people with DS extracted from the studies included in the review

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Carmeli et al., 2002[29]	CG: 10 (mean age: 63.5 ± 2.0 years) DS: 16 (63.3 ± 4.8)	To compare isokinetic leg strength and dynamic balance after and before treadmill training.	Treadmill walking program lasting 6 months	Improvements on knee extension and isokinetic flexion strength.
Ulrich et al., 2004[30]	DS: 12 (8–10 years) CG: 12 (8–10 years)	Compare the global levels of stiffness and force.	Walking on a treadmill at speeds slower and faster than preferred.	Both groups adapted to imposed speed increases similarly by increasing their global stiffness and angular impulse. Higher angular impulse values for children with DS.
Kubo et al., 2006[46]	CG: 10 (8–10 years) DS: 12 (8–10 years)	Assessing pelvis and HAT movements and their coordination during treadmill walking in the AP and ML directions.	Walking on a treadmill at 40%, 75% and 110% of preferred walking speed.	Higher kinetic energy ratio in mediolateral direction.
Gomes et al., 2007[31]	CG: 9 (19–29 years) DS: 9 (19–29 years)	Examine the effects of visual and somatosensory information on body sway.	Stood in upright stance in four experimental conditions: no vision and no touch; vision and no touch; no vision and touch; and vision and touch.	Both groups used vision and touch to reduce overall body sway. Individuals with DS still oscillated more.
Galli et al., 2008[11]	CG: 30 (5–13 years) DS: 98 (6–15 years)	Comparison of kinematic and kinetics variables between groups.	None.	Increased peak hip flexor moment at initial contact. Increased hip extensor moment in stance phase. Ankle: short dorsiflexor peak at beginning of stance phase and reduction in peak ankle moment; great hip rigidity.

Table 3. Continued

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Rigoldi et al., 2009[22]	DS: 9 CG: 10 Children (age not available)	Associate cerebral volumes with walking characteristics.	None.	Lower power during terminal stance. Decreased peak dorsiflexion/plantar flexion moment; lower ankle generated power.
Cimolin et al., 2010[1]	DS: 21 (18–39 years) PW: 19 (17–40 years) CG: 20 (33.4 years)	Comparison of kinematic and kinetics variables between groups.	None.	Reduced push-off force during terminal stance. Greater hip and knee stiffness. Lower peak ankle power during terminal stance. Greater hip and reduced ankle stiffness.
Rigoldi et al., 2011[2]	DS groups: 10 children (9.2 years), 15 adolescents (16.7 years), 16 adults (37.3 years); CG (mean age: 8.1, 18.0 and 37.6 years, respectively)	Comparison of kinematic and kinetics variables between groups.	None.	Reduction in peak ankle dorsiflexion/plantar flexion moment and related generated power; higher hip-generated power; reduction in power of knee and ankle.
Rigoldi et al., 2012[22]	DS: 16 (31–45 years) ED: 12 (36–59 years) CG: 20 (30–50 years)	Comparison of kinematic and kinetics variables between groups.	None.	Greater hip-generated work. Less ankle-generated work. Greater hip and reduced ankle stiffness.
Salami et al., 2014[13]	DS: 21 (18–29 years) CG: 18 (21–30 years)	Comparison of kinematic and kinetics variables between groups.	None.	Lower external kinetic energy in both conditions.
Wu et al., 2010 [21]	DS: 10 (9.1 years) CG: 10 (9.3 years)	Comparison of kinematic and kinetics variables between groups.	None.	Harmonics of power spectrum showed similar frequencies in DS and CG groups.
Wu et al., 2014[23]	DS: 10 (7–10 years) CG: 10 (7–10 years)	To investigate the effect of both walking speed and external ankle load on the kinetic patterns of treadmill walking.	Treadmill speeds were set at 75% and 100% of the preferred walking speed.	At faster treadmill speed, increase in propulsion duration, unloading rate and vertical propulsive impulse.Age is expressed as range or mean, according to availability. CG: control group; DS: Down syndrome; NA: not available.

Age is expressed as range or mean, according to availability.
CG: control group; DS: Down syndrome; NA: not available.

Higher levels of stiffness and angular impulse when walking on the treadmill were also exhibited by children with DS[33]. This is a typical strategy of the development of individuals with DS seeking to compensate for muscle weakness and thus to optimize poor postural control.

Eleven studies reported data on postural control collected on a population of more than 500 individuals with DS ranging from toddlers to 50 years (Table 4). In general, mediolateral body sway was greater and more variable among toddlers undergoing gait training[23], as well as when training was conducted on an unstable foam rubber mat over a pressure plate[15]. Consistently, higher and more variable mediolateral and anteroposterior displacement of the center of mass at different walking speeds (especially at faster speeds) was found in patients with DS[15, 17, 44, 45]. A similar trend was also found in adults with DS compared to children with DS[42], as the children exhibited less mediolateral CoP sway, with no differences found between the conditions of eyes open and eyes closed[44, 47]. Conversely, greater mediolateral CoP sway and velocity were observed with eyes open relative to a control group in two studies[42, 44]. In addition, larger CoP displacement in the mediolateral direction, CoP trajectory length and sway frequency in the mediolateral and anteroposterior directions were found, with no differences between the conditions of eyes open and eyes closed[40–42].

In addressing these issues, three months of sensory-motor training resulted in better balance, and improved control of the center of gravity within a 13-mm radius in conditions of eyes open and eyes closed[43]. Eid et al. investigated the effects of isokinetic training on muscle strength and postural balance in children with DS, obtaining improvements in postural balance and peak torque of knee flexors and extensors[38].

Some clinical trials proposed interventions mitigating the deviation from normal in terms of spatiotemporal gait variables[24]. Among the different types of interventions, postural insoles showed an overall beneficial effect in children with DS aged one to six years, resulting in increased gait velocity and step length, with a consequent reduction in cadence. These

Table 4. Postural control features extracted from selected studies

Study	Sample size and age	Evaluation aim	Intervention	Main outcomes in the DS group
Webber et al., 2004[39]	DS: 9 (19–38 years) CG: 9 (21–40 years)	Postural control assessment.	None.	Greater stiffness, higher with eyes closed. Greater sway velocity.
Galli et al., 2008[40]	DS: 60 (16–22 years) CG: 10 (19–25 years)	Postural control assessment.	None.	Greater ML excursion, trajectory length of COP and frequencies in ML and AP directions.
Cimolin et al., 2011[14]	DS: 19 (25.7 years) CG: 20 (29.1 years)	Postural control assessment.	None.	Greater sway amplitude in ML and AP directions with EO in comparison to CG.
Rigoldi et al., 2011[42]	DS children: 37 (6–11 years). DS adolescents: 58 (12–19 years). DS adults: 45 (22–46 years). CG children: 10 (5–11 years). CG adolescents: 15 (13–20 years). CG adults: 16 (29–50 years).	Postural control assessment.	None.	Larger movement frequency in ML direction in the adult group. ML excursion of COP diminished from children to adults (both EO and EC).
Cabeza-Ruiz et al., 2011[41]	DS: 27 (27.4 years) CG: 27 (23.4 years)	Postural control assessment.	None.	Poorer static balance control. Greater COP trajectory.
Villarroya et al., 2012[47]	DS: 32 (10–19 years) CG: 33 (10–19 years)	Postural control assessment.	None.	Greater COP displacement in AP and ML directions. Greater COP velocity and median frequency. Larger COP sway path.
Wang et al., 2012[44]	DS: 23 (14.4 years) CG: 18 (13.8 years)	Postural control assessment.	None.	DS: greater displacement and higher velocity of COP sway during quiet standing. EO: Greater COP velocity and sway in ML direction. EC: Greater COP velocity; longer reaction and movement times than in CG.
Vilarroya et al., 2013[15]	DS: 30 (11–20 years) CG: 27 (11–20 years)	Postural control assessment.	Vibration training program.	DS: Greater velocity of COP displacement. Higher values of postural parameters values (EO, EC).
Bieć et al., 2014[45]	DS: 10 (29.8 years) CG: 11 (28.4 years)	To examine postural control on hard and soft surfaces.	None.	Greater COP variability in ML direction with EO over foam cushion. Greater mean velocity of COP and frequency with foam cushion. DS with EO: greater sway in ML direction with foam cushion. Reduced ML control with EO on foam cushion. Greater sway frequency and mean velocity in AP direction.
Eid et al., 2017[38]	DS: 31 (9–12 years)	Measurement of stability indices, peak torque of knee flexors and extensors of both sides using the isokinetic dynamometer.	Two subgroups: 1) conventional physical therapy, 2) added isokinetic training 3 days a week for 12 weeks.	Greater improvements observed in group 2) regarding postural balance and peak torque of knee flexors and extensors.

Age is expressed as range or mean, according to availability.
COP: center of pressure; COG: center of gravity; CG: control group; DS: Down syndrome; EC/EO: eyes closed/open; ML: mediolateral; ROM: Range of motion.

improvements were also related to the increase in age[51].

Treadmill training constitutes an important tool often used in children with DS[23, 24]: Looper and collaborators found that six children with DS demonstrated a four times wider step width upon the acquisition of gait in comparison to nine healthy children that had not already acquired mature gait. This pattern was maintained up to 12 months after gait acquisition. This study also showed that high-intensity treadmill training produced a more stable gait one month before than low-intensity training. Promising results of treadmill training were also obtained on 26 toddlers with DS, with high-intensity training leading to an earlier acquisition of gait (on average at 19.2 months) compared to low-intensity training (on average at 21.7 months)[24]: although both low and high training intensity resulted in an increase in hip and knee peak flexion, dorsiflexion of the ankle at toe-off, and hip extension and plantar flexion of the ankle in the late stance, these effects were greater in the group undergoing high-intensity training during the follow-up evaluation. An 8% to 13% improvement in hip adduction was also found after toe-off, with a consequent reduction in the abductor pattern. On the contrary, adults with DS (n=15) showed minimal changes in comparison to healthy individuals (n=15) after being submitted to multiple sessions of treadmill training at different speeds[17]. However, improvements on knee extension and flexion isokinetic strength and on dynamic balance performance after training was observed in elderly with DS after and before a treadmill training for 6 months[32].

DISCUSSION

Ligament laxity, hypotonia and cognitive delay presented by DS directly influence the development of compensatory strategies in the movement and postural control[9, 49, 50]. During childhood, the considerable variability of gait parameters[2, 11, 37] can be explained by the incomplete maturation of the locomotor system. This pattern results in an augmented energy expenditure associated to locomotion.

In addition, smaller step length and larger step width are shown by children and adolescents with DS when compared to healthy individuals. These impairments reduce throughout life, following the improvement of postural control and movement[2, 5, 6, 8, 11, 12, 16, 37]. In that, some change was observed during lifespan: during childhood, larger variability in gait parameters was observed[2], and the spatiotemporal locomotor traits were consistent with the gait profile of DS patients[34]. After this age (>12 years) people with DS tend to develop strategy focused on the reduction of the degrees of freedom (ranges of motion), in an attempt to compensate for muscle weakness and gain better postural control. This produces an increasing dispersion of generated power in the frontal plane and consequently enhances the cost of locomotion[51]. On the contrary, healthy participants exploited full joints amplitude, in order to gain a more efficient motion in the sagittal plane[2].

Spatiotemporal abnormalities as reduced gait velocity and step length or larger step width were frequently linked to a reduction in the range of motion of all lower limb joints[1, 11, 41]. The main kinematic abnormalities were an increase in hip flexion throughout the entire gait cycle, an increase in knee flexion in the stance phase, ankle stiffness, a reduction in peak plantar flexion at pre-swing phase and a reduction in peak dorsiflexion in the initial stance phase[1, 2, 11, 14, 22].

These findings are considered to be induced by neuromuscular abnormalities in individuals with DS, which involves hypotonia, muscle weakness and ligament laxity[1, 6, 11], alongside neurological impairments affecting stability and motor control[6, 36].

Focusing on gender-related differences, women exhibit a larger hip flexion at late stance and reduced knee flexion at the beginning of the swing phase, shorter step length and higher GPS than in male patients[32, 33]. These findings are likely due to the weakness of the hip flexors and of the abdominal muscles typical of women with DS.

These kinematic abnormalities might reflect a diminished power of ankle movement during the initial stance and pre-swing phases: the compromised plantar flexion power of the ankle leads to a reduced propulsion capability throughout the swing action.

The reduction in gait velocity and step length, together with the increase in step width, are meant to provide stability throughout the increase in the body base of support[39, 42, 43, 47]. Indeed, individuals with DS tend to show greater body sway in the mediolateral direction, which triggers an increase in step width as a mean to maintain the center of gravity over the base of support. These adaptive strategies, which in principle are not considered as normal, can be corrected in the process of gait maturation in patients with DS if proper intervention is provided early[22–24, 37].

It is likely that in DS joints stiffness increases during the acquisition of gait in an attempt to ensure stability, resulting in a reduction of lower-limb joints ranges of motion[1, 11, 22, 39]. Also the increase in hip flexion throughout the entire gait cycle and in knee flexion in the stance phase are probably the consequence of a lower limb stiffness[2, 11, 22, 36]. For instance, a higher knee flexion at initial contact can be explained by the absence of the first peak in the knee extension moment, which is indicative of muscle weakness, thereby impairing knee joint stabilization[11, 36, 39]. This alteration does not correspond to an extensor moment and suggests insufficient strength of the knee extensors, which is necessary to stabilize the knee during the stance phase. Thus, the increase in ankle plantar flexion at initial contact can be interpreted as a compensatory strategy for controlling knee extension[11, 40].

Postural instability in DS was characterized by greater displacement of the center of mass during gait and of the center of pressure during quiet standing[14, 39, 40, 44]. In DS, postural instability is likely the result of compromised structures of the central nervous system, such as the cerebellum, associated with the neuromuscular impairments typical of this syndrome[6, 36]. Ankle stiffness might produce a global inefficient balance strategy, requiring an adequate range of motion in terms of dor-

siflexion and plantar flexion for the efficient maintenance of anteroposterior stability in the standing position. As the ankle stiffness strategy is generally not enough to maintain stability during quiet standing, a balance strategy involving the hip was adopted, resulting in greater displacement of the center of pressure in the mediolateral direction[11, 14, 17, 26, 40, 45].

Although a small number of studies were found on the relationship between cerebellar abnormalities in individuals with DS and gait abnormalities, we believe that such characteristics might lead to the movement pattern seen in these patients[9]. Only one of the included studies demonstrated an intriguing connection between the volume of the cerebellar vermis and gait pattern in adults with DS[36]. The Authors claim that a larger cerebellar vermis volume—closer to the range of normality—is related to a kinematic gait pattern closer to normalcy. There is an evident need to develop further studies on this issue to clarify the real impact of cerebellar abnormalities. Individuals with abnormal postural control to adapt their own motor strategies with the goal of acquiring an independent gait function, even if such independence is obtained through inappropriate biomechanical compensations[52]. Thus, a cascade of alterations occurs in the movement pattern of people with DS, which is constantly reinforced during the act of walking[1, 6, 11, 14, 16, 35, 36, 40].

Among the intervention strategies described in the literature, high-intensity treadmill training is one of the most promising, if training duration, training speed and ankle weight are increased over time. Superior effects of intensive training were shown in comparison to low-intensity training, including the acquisition of gait at an earlier age (approximately one month prior to children submitted to low-intensity training) and improved stability during this locomotor function[22–24, 37]. Intensive gait training produces better effects in children and adolescents with DS, but the effects on adults are limited and offer little evidence of greater gains. Some authors suggested that an increase in the velocity of treadmill training could result in the worsening of abnormal spatiotemporal gait variables, such as an increase in step width and reduction in step length[6, 53].

Benefits of equotherapy (thirteen sessions, 50 minutes per day) for children with DS were also found, with positive changes in the angular kinematics of the ankle joint after the therapeutic intervention[54]. Strength training also showed promising results in DS: after a 6-week progressive resistive exercises for lower limbs and balance training, the intervention group showed a significant improvement in the lower limb strength (knee extensors, hip flexors) and in the balance compared to a control group[55].

Based on these findings, we believe that including treadmill training sessions into the rehabilitation process of children with DS should occur even before the acquisition of gait, with the therapist assisting and guiding the patients throughout the accomplishment of this task. For a child with delayed motor development, acquiring gait and perfecting stability during gait could result in a better exploration of the surrounding environment, which in turn provides ample benefits for the child, reduces the risk of falls and increases social interaction. If well planned, intensive training can be a facilitating factor to improve body stability, as it gives the child the opportunity to train the different aspects of gait repeatedly, which can contribute positively to motor learning with regard to the different phases of the gait cycle[1, 53]. Walking on a treadmill induces the patient to exercise gait in a rhythmic fashion that requires the motor strategies to cope with gait velocity, as locomotion speed can be tuned by the therapist. Moreover, step length and width are constrained by the dimensions of the treadmill, which makes a marked increase in step width unviable[53, 56]. Such benefits are more evident in studies involving children.

Concrete chances arose of adjusting gait variables during ages recognized for their sensitivity to motor learning—before the gait pattern is fully established at higher neurological levels[57]. Once a gait pattern is acquired, patients would have to re-motor strategies that are already consolidated at higher levels of the central nervous system. This is why adults are less sensitive to learn new motor strategies. There can even be a risk that treadmill training could reinforce the existing pattern, which is altered in individuals with DS, and the increase in treadmill velocity would only result in harder training, producing inappropriate compensatory strategies.

Three main limitations were identified in the reviewed body of literature: (1) several studies analyzed relatively small cohorts, hindering the generalizability and the statistical power of results; in addition, the existence of any regional specificity is still to be addressed. Further (2), we noticed a lack of pre- and post-intervention trials, that are advisable to produce evidence-based indications on rehabilitation outcomes. In addition, future research directions should address the synchronized use of electromyography and electroencephalography, in order to synchronously evaluate the muscular and cerebral activities during the performance of activities. These physiological data are scant in DS and could further enhance the therapeutic tools and rehabilitation outcomes in all stages of life. At last (3), we did not find relevant studies on the gait decline in people with DS: since it is known that in patients with cognitive impairments the gait function disrupts with age more markedly than in healthy individuals[58, 59], systematic research on the decline of functional locomotor abilities associated to early ageing is advisable.

In conclusion, patients with Down syndrome exhibit altered spatiotemporal gait variables, especially in the first years of life. Intensive rehabilitation programs, as treadmill and strength training at an early age seem to result in durable long-term improvements, with fewer compensatory patterns during movement, improving stability during locomotion and postural control throughout life. While the main features of gait can be considered today largely understood, directions of future research should investigate the impact of the cognitive function and neuromuscular control on these motor traits. Lastly, a promising avenue for future trials is to quantify the beneficial effects of the exposure of these patients to an enriched environment, involving social/recreational activities such as participation in sports.

Conflict of interest

The authors declare that they have no competing interest.

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