Mechanical energy assessment of adult with Down syndrome during walking with obstacle avoidance

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1. Introduction

Motor disability is widespread among individuals with Down Syndrome (DS). From the literature it is well-known that subjects with DS present neuromotor alterations that result in altered movement patterns, of which slowness, longer reaction times, instability, and patterns of muscular co-contractions are some of the most recurrent features (Almeida, Corcos, & Latash, 1994; Aruin & Latash, 1996; Rigoldi, Galli, & Albertini, 2011; Rigoldi, Galli, Mainardi, Crivellini, & Albertini, 2011b; Vimercati, Galli, Rigoldi, Ancillao, & Albertini, 2013). Given these motor difficulties and the self-perceived instability of their movements, subjects with DS tend to trade movement efficiency with movement safety (Vimercati, Galli, Rigoldi, Ancillao, & Albertini, 2011; Vimercati et al., 2013), and as a consequence of both neuromotor deficits and safety strategies

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their movements appear "clumsy" respect to the normal population (Latash et al., 1996; Latash, 1992, 2007; Rigoldi et al., 2012).

If most of the studies in literature considered plane walking and standing, a growing interest has been observed in recent literature for studies regarding more complex, functional movements, such as clearing an obstacle while walking. Walking in fact is a motor task that is highly flexible in its adaptation to different situations. Successful interaction with the environment requires the adaptation and combination of fundamental locomotion skills, and this ability to combine movement is essential to daily living (Pearson & Gramlich, 2010). While obstacle crossing is not so challenging in normal gait, obstacles present a significant hazard to persons with neuromotor disabilities, such as DS, who present an increased risk of falls (Virji-Babul & Brown, 2004).

Among the few numbers of studies focused on obstacle avoidance in persons with DS (Virji-Babul & Brown, 2004), studied the mechanism of anticipatory control of gait in relation to the perception of an obstacle. The study was performed in two different conditions: stepping over a subtle obstacle that was placed at a very low distance from the floor (1% of total body height), and an obvious obstacle that was placed at a much higher distance from the floor (15% of total body height). Virji-Babul and Brown (2004) found that subjects with DS are able to extract information about obstacle height and match this information to their movement. However, this information was used without preparing subjects for trials. Vimercati, Galli, Rigoldi, and Albertini (2012) studied the spatiotemporal and kinematic features of obstacle avoidance in teenagers and young adults with DS and in an age-matched control group. They demonstrated that the presence of a destabilizing element, such as the obstacle, enhanced different motor strategies in DS compared to Normal (N), as shown by the parameters of the lower limbs, with a stabilization and safety strategy adopted by DS at the upper limbs. Major differences were found for the pelvis and hip joints patterns in DS compared to controls; while control subjects modified their movement only in the main plane of movement (i.e. sagittal plane) persons with DS displayed a different strategy, with increased values for the sagittal, frontal and horizontal planes. The presence of an obstacle enhanced stabilization and safety strategies at the upper limbs, which were elevated forward and outward in an attempt to stabilize the center of mass and to prevent for possible falls. Despite similar foot elevation, people of control group exploited the elevation to progress forward (longer step lengths) while people with DS did not exploit the elevation to land with their foot further (they produced shorter step lengths). Provided that obstacle avoidance is more expensive, in terms of energy consumption, than plane walking (Chou, Draganich, & Song, 1997), the authors speculated that the "unexploited" limb elevation and different clearing strategies in people with DS led presumably to a less efficient clearing than in controls. However, no measurement about either metabolic or mechanical energy consumption is present in the literature in relation to walking with obstacle avoidance in patient with DS.

Human locomotion involves smooth advancement of the body through space in order to minimize mechanical and physiological energy expenditure. While the goal of walking is progression in the forward direction, limb motion is based on the need to maintain a symmetrical, low amplitude displacement of the center of gravity of the head, arms, and trunk in the vertical and lateral directions. This conserves both kinetic and potential energy and is the principle of biological 'conservation of energy' (Waters & Mulroy, 1999) that is an efficient gesture. In normal gait, the energy cost, expressed in $J\,kg^{-1}\,m^{-1}$, depends mainly on gait speed and reaches a minimum at a speed which is defined as optimum, while increases progressively at speeds that are either higher or lower. Generally, subjects with different motor disabilities such as subjects with DS cannot attain a "normal" speed (Rigoldi, Galli, & Albertini, 2011; Rigoldi, Galli, Mainardi, Crivellini, et al., 2011); thus, an increase of cost of gait might well be due partly to the low speed itself. Agiovlasitis, McCubbin, Yun, Mpitsos, and Pavol (2009) suggested a gait pattern with lesser stability and greater energetic cost among adults with DS, particularly at fast speeds. The differences in the center of mass motion and stepping behaviors exhibited by adults with DS was one of the reasons why these individuals showed greater energetic cost during walking with respect to adults without DS. It has been hypothesized that the increase in energy cost could be also related to abnormal kinematics of the lower limbs that disturb the smoothness sinusoidal displacement of the CM (Center of Mass), increasing the mechanical work done to move the CM and disturbing the efficiency of the pendulum-like mechanism (Tesio, Roi, & Moller, 1991).

Given the different movement strategies adopted by subjects with DS when clearing an obstacle and given the lack of studies in the literature regarding evaluation of mechanical energy consumption during obstacle avoidance in people with DS, the aims of this study were (i) the analysis of the differences between the safer condition of plane walking and the less safe condition of stepping over an obstacle within the context of an existing pathology, DS, whose features imply the use of alternative and probably less efficient motor control strategies to reach the goal of maintaining equilibrium during obstacle avoidance and (ii) the comparison of movement efficiency between healthy people and people with DS in terms of energy cost.

2. Materials and methods

2.1. Participants

The study was approved by the ethical committee of IRCCS San Raffaele Pisana, Tosinvest Sanità, Rome, where the walking trials for data capturing took place. The subjects and their legal tutors gave their informed consent to the study. A total of 39 individuals were included in our study, 21 subjects with DS (the mean age: 21.6 ± 7 years and the age range: 18–29 years) and one control group (*N*) of 18 subjects (the mean age: 25.1 ± 2.4 years and the age range: 21–30 years) with no motor or cognitive deficit. Mean age, height, and weight were obtained for each group (Table 1). Inclusion criteria for the people in DS group were adult age, no severe obesity (normal to overweight Body Mass Index, $18.5 < BMI < 30$), low to medium intelligence quotient

Table 1
Overview of the subjects' characteristics (mean ± SD); age, height, weight, and number of subjects.

	DS	N
Age (years)	21.6 ± 7	25.1 ± 2.4
Height (m)	1.52 ± 0.08	1.68 ± 0.07
Weight (kg)	56 ± 9.1	60 ± 7.5
Number of subjects	21	18

(35 < IQ < 70), no clinical sign of dementia, no orthopedic problems. Inclusion criteria for *N* subjects were adult age, no severe obesity (normal to overweight Body Mass Index, 18.5 < BMI < 30), no clinical sign of dementia, no orthopedic problems, no reported motor and/or neurological disorders.

2.2. Acquisition and instrumentation

The subjects walked along a walkway of approximately ten meters length in two conditions: plane walking (wlk) and walking with an obstacle (10% of the subject's height, obs). All participants were instructed to walk at a comfortable speed. The obstacle was a wooden stick, which was supported by two supports placed laterally to the walkway. The tasks were acquired using quantitative movement analysis, composed of an optoelectronic system (Elite2002, BTS) with eight infrared cameras. The optoelectronic system records the three-dimensional coordinates of the markers through time. Markers were placed on the body according to Davis' protocol (Davis, Õunpuu, Tybursky, & Gage, 1991) and two markers were put, respectively, at the two ends of the obstacle to define the obstacle position relative to the subject during the movement. Three trials were collected for each condition and the most reproducible trial, meaning the possibility for subjects to redo the same trial and obtain same results, was used for further analysis.

2.3. Parameters

2.3.1. Spatiotemporal parameters

Step length, step width, and mean velocity were computed from the markers' coordinates during walking. Step length and step width were, respectively, defined as the anteroposterior (AP) distance between two consecutive heel contacts of the feet and the mediolateral (ML) distance between two heel centers of two consecutive foot contacts (Fig. 1).

Mean velocity, which is an indicator of conservatism of the movement (Chen, Ashton-Miller, Alexander, & Schultz, 1991), was defined as the average velocity of the marker on the sacrum during walking. Also, in obs condition, mean velocity was

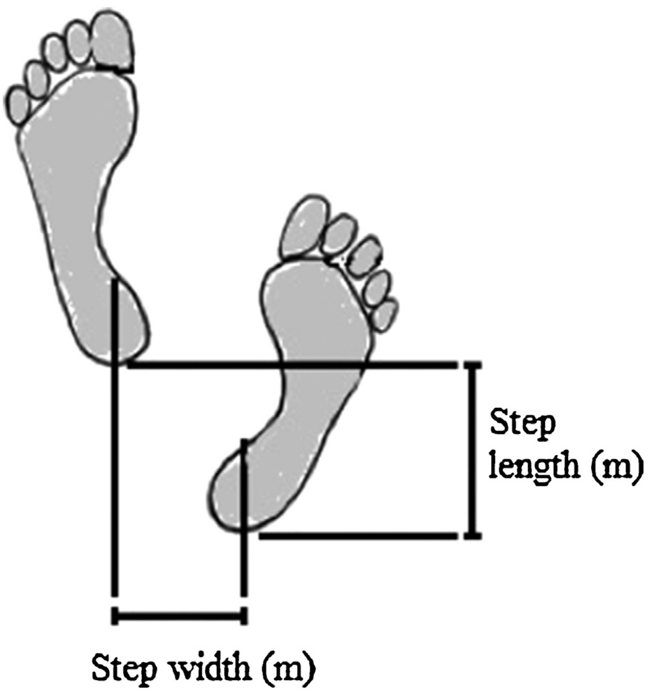

Fig. 1. Step length and step width defining during walking.

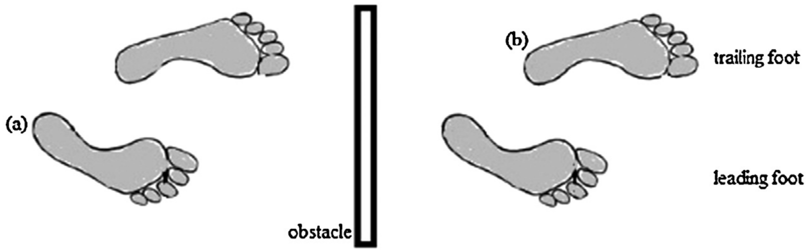

Fig. 2. (a) Last heel strike of leading foot before the obstacle and (b) the first heel strike of trailing foot after the obstacle.

defined as the average velocity of the marker on the sacrum from the last heel strike of leading foot before the obstacle to the first heel strike of trailing foot after the obstacle (Fig. 2).

2.3.2. Mechanical energy parameters

In pathological gait, as in individuals with DS, deviations in gait pattern can lead to inefficient gait. Gait efficiency is usually quantified by the assessment of energy expenditure during walking. Energy computation gives a measure of the amount of energy required to walk over a given distance.

2.3.2.1. Energy Recovery (ER). Energy recovery has been defined as difference percentage between external and internal works during stance phase of walking (Cavagna, Saibene, & Margaria, 1967). In this paper we modified this definition not only for stance phase but also for whole cycle by computing mechanical energy exchanges. Mechanical energy exchanges despite of metabolic energy do not need steady state conditions and it has reproducibility ability (1).

Mechanical energy consists of two main components, kinetic energy and potential energy. In the literature, different approaches have been introduced to estimate mechanical energy (Van de Walle et al., 2011).

In this study, center of mass approach has been used to estimate mechanical energy exchanges. In this regard, the following quantities were computed:

- First and second kinetic energy picks including two max (MaxK1, MaxK2) and two min (MinK1, MINK2) in each gait cycle (Fig. 3).
- First and second potential energy picks including two max (MaxP1, MaxP2) and two min (MinP1, MINP2) in each gait cycle (Fig. 4).
- Total mechanical energy exchange (TME).

All of the above mentioned energy parameters have been normalized by the body mass (kg) and height (m).

These parameters also calculated for walking with avoiding obstacle. ER shows how much of the mechanical energy (sum of potential energy and kinetic energy) can be recovered due to conversion of potential energy to kinetic energy and vice versa.

$$ER = \frac{(E_P + E_K) - E_{tot}}{E_P + E_K} \quad (1)$$

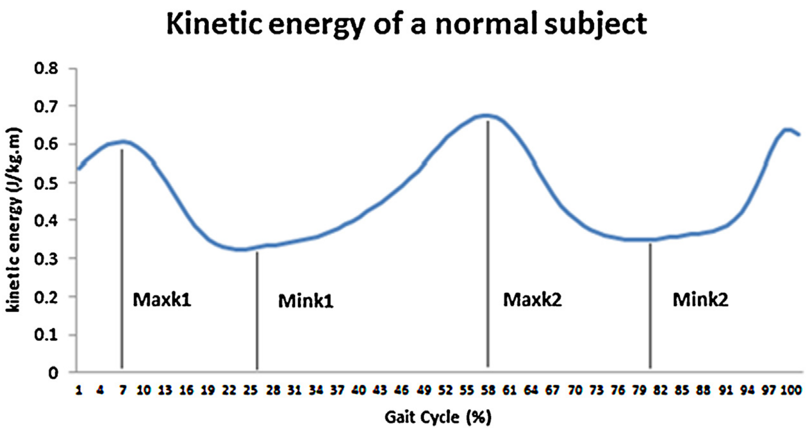

Fig. 3. Graph of kinetic energy during walking.

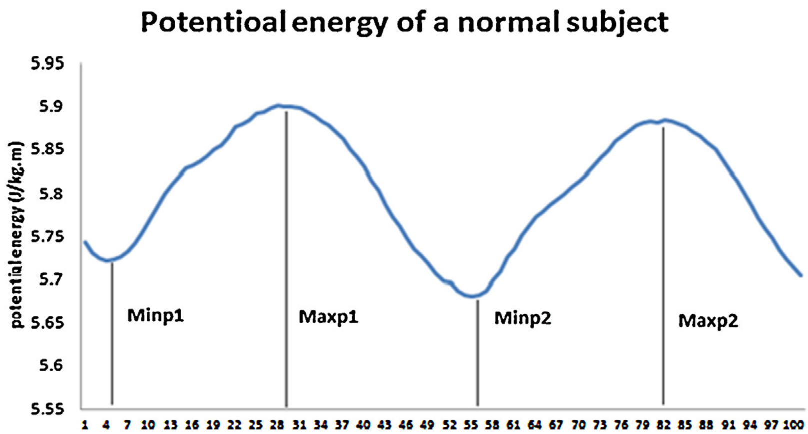

Fig. 4. Graph of potential energy during walking.

where:

$$E_p = (\text{Max}P1 - \text{Min}P1) + (\text{Max}P2 - \text{Min}P2) \quad (2)$$

$$E_K = (\text{Max}K1 - \text{Min}K1) + (\text{Max}K2 - \text{Min}K2) \quad (3)$$

2.4. Statistical analysis

At the first, Kolmogorov–Smirnov test was used for evaluation of normality of the distribution of data. Then, a 2 conditions × 2 groups ANOVA was used to analyze the presence of statistically significant differences (p-value < 0.05) between people of the two groups N and DS in the two conditions (wlk and obs).

3. Results

3.1. Spatiotemporal parameters

Table 2 shows the results of the spatiotemporal parameters (median, 25th and 75th percentile values) for plane walking and stepping over obstacle for both people of N and DS groups.

For adults with DS, compared to N, reduced and more variable (as seen by the percentiles range) step length, increased step width and decreased velocity was found in both conditions. Mechanical energy data are normalized by body weight (kg) and body height (m).

N reduced velocity and increased step width in the obs condition compared to the wlk condition. People with DS increased step width but maintained other parameters unvaried across conditions.

3.2. Energy recovery (ER)

The punctual parameter computed on potential energy and kinetic energy traces have been used to calculate the ER, which has a clear clinical meaning for comparing the groups and conditions. ER parameter reveals that which group of subjects can better recover the mechanical energy that because it is difficult to separate stance phase for people with DS completely during wlk and obs, it is consumed in the gait cycle. In both conditions, people with DS walked with the same ER value respect to N. But ER value changed across conditions for both groups (Table 3).

Table 2
Median (25th percentile, 75th percentile) values of the spatiotemporal parameters, wlk: plane walking condition, obs: stepping over obstacle.

	wlk		obs		
	N	DS	N	DS	
Step Length (m)	0.586 (0.569, 0.611)	0.422 (0.379, 0.457)	0.603 (0.561, 0.640)	0.415 (0.340, 0.485)	§, *
Step Width (m)	0.152 (0.147, 0.177)	0.199 (0.179, 0.217)	0.210 (0.197, 0.226)	0.242 (0.226, 0.275)	§, *, #, +
Mean Velocity (m/s)	1.204 (1.125, 1.265)	0.658 (0.598, 0.730)	1.054 (1.003, 1.166)	0.597 (0.470, 0.672)	§, *, #

§ Significant difference between N-wlk and DS-wlk (p-value < 0.05).
* Significant difference between N-obs and DS-obs (p-value < 0.05).
\# Significant difference between N-wlk and N-obs (p-value < 0.05).
\+ Significant difference between DS-wlk and DS-obs (p-value < 0.05).

Table 3
Median (25th percentile, 75th percentile) values of the mechanical energy parameters, wlk: plane walking condition, obs: stepping over obstacle.

	wlk		obs		
	N	DS	N	DS	
MaxP1 (J/kg m)	5.467 (5.418, 5.541)	5.491 (5.403, 5.608)	5.475 (5.397, 5.609)	5.394 (5.273, 5.597)	
MaxP2 (J/kg m)	5.466 (5.418, 5.540)	5.516 (5.411, 5.612)	5.517 (5.492, 5.656)	5.552 (5.371, 5.666)	
MinP1 (J/kg m)	5.255 (5.175, 5.331)	5.355 (5.189, 5.453)	5.265 (5.202, 5.349)	5.257 (5.109, 5.490)	
MinP2 (J/kg m)	5.256 (5.135, 5.312)	5.330 (5.190, 5.422)	5.257 (5.173, 5.320)	5.258 (5.002, 5.362)	
MaxP1–MinP1 (J/kg m)	0.214 (0.194, 0.244)	0.173 (0.114, 0.198)	0.224 (0.185, 0.264)	0.187 (0.143, 0.232)	§, *
MaxP2–MinP2 (J/kg m)	0.239 (0.200, 0.256)	0.197 (0.159, 0.228)	0.318 (0.272, 0.357)	0.309 (0.234, 0.381)	*, #, +
MaxK1 (J/kg m)	0.647 (0.567, 0.720)	0.303 (0.249, 0.380)	0.565 (0.457, 0.685)	0.252 (0.177, 0.331)	§, *
MaxK2 (J/kg m)	0.662 (0.582, 0.720)	0.305 (0.253, 0.395)	0.567 (0.456, 0.794)	0.252 (0.177, 0.346)	§, *
MinK1 (J/kg m)	0.372 (0.315, 0.413)	0.102 (0.090, 0.167)	0.230 (0.116, 0.274)	0.076 (0.012, 0.100)	§, *, #, +
MinK2 (J/kg m)	0.332 (0.294, 0.398)	0.093 (0.075, 0.150)	0.141 (0.099, 0.206)	0.019 (0.005, 0.041)	§, *, #, +
MaxK1–MinK1 (J/kg m)	0.272 (0.251, 0.303)	0.195 (0.139, 0.210)	0.324 (0.226, 0.410)	0.168 (0.110, 0.241)	§, *
MaxK2–MinK2 (J/kg m)	0.303 (0.278, 0.341)	0.210 (0.164, 0.238)	0.437 (0.308, 0.559)	0.221 (0.172, 0.312)	§, *, #
ER (%)	57.7 (52.8, 62.12)	59.7 (53.8, 65)	47 (41.4, 49.4)	43.33 (37.1, 53.5)	#, +

§ Significant difference between N-wlk and DS-wlk (p-value < 0.05).
* Significant difference between N-obs and DS-obs (p-value < 0.05).
# Significant difference between N-wlk and N-obs (p-value < 0.05).
+ Significant difference between DS-wlk and DS-obs (p-value < 0.05).

3.3. *"Mechanical energy recovery informed": additional results*

As reported by the literature and observing the different strategies used by the two groups in term of spatiotemporal parameters, we expected different ER values for both groups and conditions.

ER parameters instead revealed no differences between people in DS and N groups and between wlk and obs. Given that the ER parameter is composed by different punctual indexes computed on potential, kinetic and total energy, we statistically analyzed the contributions of each component. In Table 3 the results of the statistical analysis were reported.

As shown in Table 3 except for MaxP1–MinP1 and MaxP2–MinP2, which are higher for people in N group respect to people with DS in obs condition, there are no significant differences in the other potential energy parameters between people in DS and N groups within conditions. On contrary, all of the kinetic energy parameters between people in DS and N groups differ in both of wlk and obs conditions. In other words, people with DS walked with lower kinetic energy than people in N group in both conditions. Also, MinK1 and MinK2 parameters are different between two conditions for both of two groups. But for ER parameter we have significant differences between obs and wlk in both groups. In N group, ER decreases about 18.5% through walking to obstacle stepping and for people in DS group, this amount is 27.1%.

4. Discussion and conclusion

This work is the first study to provide quantitative evidence for mechanical energy expenditure in persons with DS during the challenging and safety-threatening situation of obstacle avoidance during walking. Since obstacle avoidance requires balance and high motor control abilities, it is of particular interest to evaluate this task in a population, such as DS, where movement efficiency is reduced and safety, not task accomplishment, is put as the first goal during movement execution.

We found that, in all conditions, mean velocity and step length were significantly lower in people with DS respect to N group and step width was larger, features of DS that are well-documented in the literature and that can be seen as a strategy to increase stability when situations of unbalance and instability are present (Rigoldi, Galli, & Albertini, 2011; Rigoldi, Galli, Mainardi, Crivellini, et al., 2011; Vimercati et al., 2011, 2012). Variability was higher across all conditions for people in DS group compared to people N group. The presence of instability may be linked to the increased risk of falling in DS, as reported by Virji-Babul and Brown (2004) and by Judge, Davis, and Ounpuu (1996), who found that step length has an inverse relationship with falling risk.

In addition, a short step reduces the biomechanical demands (smaller AP momentum in joints due to smaller AP force during landing (King, Luchies, Stylianou, Schiffman, & Thelen, 2005)), which may be preferential for subjects with DS who have reduced motor and physical capacities compared to N subjects.

From our results mechanical energy recovery during walking for healthy subject had good correspondence with previous studies (Cavagna, Thys, & Zamboni, 1976; around 63%).

ER was similar for both of N versus DS groups either during plane walking or stepping over obstacle but it showed intra-group differences between plane walking and walking with obstacle for both groups. The formula that was used for the computation of ER consists of three main components: the range of potential energy exchange, the range of kinetic energy, and the range of total mechanical energy of the body. In its turn, kinetic energy depends on mean velocity, and potential energy exchange depends on the vertical displacements of the center of mass. During both conditions, people with DS walked with lower velocity (lower E_K) and lower E_P than people in N group. On the other hand, for people with DS, the amount of E_{tot} was smaller compared to people in N group too. The interaction of three above mentioned sets of parameters results in very close ER values for both groups. In addition, each group had similar ER values across different conditions. It is possible to use the same line of reasoning to explain this event. As mentioned earlier, in each gait cycle, potential energy and kinetic energy are converted to each other like the mechanism of a hanging and inverted pendulum system. During each gait cycle, some of mechanical energy (sum of potential and kinetic energies) is converted into other forms of energy such as thermal energy (waste), and some can be recovered. ER is an energy parameter which indicates how much of total mechanical energy can be recovered during a gait cycle (Cavagna et al., 1976). Although DS used different strategies to walk and to step over the obstacle respect to those used by healthy subjects, with differences in the spatiotemporal parameters, as found in this study and in previous studies by Vimercati and colleagues (2012) and with differences in the kinematic parameters, as documented by Vimercati and colleagues (2011) our study highlights that they probably used their residual abilities in the most efficient way, achieving the main goal of an efficient mechanical energy recovery. Results show although people with DS has different obstacle avoidance pattern in comparison with people in N group but their ER is the same. Due to the mechanical parameters assessment, people with DS probably use different strategies to optimize mechanical energy exchanges during walking and to minimize the wasted energy during walking. As mechanical energy exchanges parameters are related to the Spatiotemporal parameters, body positions and muscle activities then this study indicates engineers and medical staff should consider quantitative assessment of not only DS but also other types of pathologies from mechanical point of view. Considering ER in gait analysis helps therapists to apply new strategies in rehabilitation methods to optimize mechanical energy exchanges during walking as much as possible. Further studies should include the role of the upper limb in the mechanical energy calculation, since the upper limbs seemed to play an important stabilizing role in the study by Vimercati and colleagues (2011), and should compare mechanical energy consumption with metabolic energy consumption in DS. This may provide interesting information on the efficiency of movement in DS.

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