

A stair-climbing test for ambulatory assessment of children with cerebral palsy

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Abstract

The purpose of this study was to develop a stair-climbing test to measure energy cost (EC) and mechanical efficiency (ME) in children with cerebral palsy (CP) to evaluate ambulation-related motor function and its changes after intervention or maturation. Five normally developed (ND) and 10 children with CP were tested. The gross ME (ME_g) was calculated from the work done (W) and the total energy cost (oxygen consumption) measured while repeatedly ascending and descending four steps for ≈5 min without subtracting the resting metabolic rate. The ME_g was significantly lower in CP than ND (3% versus 20%, $P < 0.001$). The test was repeated in the 10 children with CP after a 4-month therapy recess. The ME_g values correlated with the initial tests, with a small, significant increase of 2%. When calculating net ME (ME_n) from W and the energy cost above resting, the correlation of ME_n values before and after therapy was inferior to that using ME_g values. Similarly, individual ME values obtained by estimating energy cost from the increase in heart rate (HR) during stair-climbing also correlated poorly, with large variability. These results show that ME_g may be used to evaluate changes in motor function resulting from age-related development or therapy. ME_g is as good or superior to ME_n; the extra time required to obtain resting energy cost and heart rate values is not necessary when measurements are desired within the same individual.

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1. Introduction

Cerebral palsy (CP) is a motor and postural disorder resulting from a non-progressive lesion in the central nervous system [1]. This lesion is a result of impaired or abnormal development of the immature brain [2] that impairs motor functions such as walking and other motor functions. Walking is the primary form of locomotion in humans and therefore a mechanically efficient gait facilitates daily activities.

Tests are often necessary to provide evidence that various rehabilitation interventions of children with CP have improved motor performance and ambulation, taking into account their natural development. This improvement is particularly difficult to interpret in a population of children with

CP because independent of the rehabilitation effect there is simultaneous on-going motor development related to age and to the type and extent of the brain lesion.

Walking efficiency is sensitive to gait abnormalities and motor control, as evidenced by children with CP having a greater oxygen cost of walking than children with muscular dystrophy or healthy children [3]. Jones and McLaughlin found a significantly lower mechanical efficiency (ME) at maximum workload on a bicycle ergometer in children with CP than in able-bodied children, emphasizing the transfer of the difficulty to a non-ambulatory task [4]. Unnithan et al. determined that much of the increased energy cost (EC) of treadmill walking in children with CP could be explained by increased mechanical power of body segments not essential to the task, but a component of the increased cost was still left unexplained [5].

The climbing and descending of stair steps is a special case of locomotion, differing mechanically from walking.

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The differences are manifested in a significant increase in the ranges of movement of the lower limbs and in more intense muscular activity causing the generation of larger forces and moments in the joints, especially in the vertical direction [6].

The measurement of the energy cost of locomotion is increasingly used to assess the effectiveness of therapeutic interventions in children with neurological impairment [7]. Changes in energy requirements of activities are commonly measured following surgery, medical treatment, physical therapy or treatment or to determine the mechanical advantage of splints and walking aids. The energy cost is derived from the oxygen consumption ($\dot{V}O_2$) required by the activity, which can be conveniently measured by open circuit expired gas collection and analyses. It is usually indexed to body weight or body surface area.

Stair-climbing, like walking on the level, is rhythmical and involves similar joints, muscles and motor planning. The purpose of this study was (a) to develop a functional test, based on energy cost measurements of a work task related to locomotion, which might serve to specifically and conveniently evaluate performance changes in ambulation in children with CP, (b) to compare the results of this test in children with CP with normally developed (ND) children and (c) to determine whether this test was repeatable and might detect changes in children with CP occurring after a 4-month recess in neurodevelopmental therapy.

2. Methods and procedures

2.1. Research subjects

Ten children (seven boys, three girls) with CP of different types and varying degrees of functional disability, and five ND children (all girls), took part in the study. Their basic anthropometric and descriptive data are summarized in Table 1. The division into groups based on functional limitation was done in accordance with Palisano et al. [8]. The Gross Motor Function Classification System (GMFCS) consists of five ordinal levels of motor function based on self-initiated movement with particular emphasis on sitting and walking. The distinction between different levels of motor function is based on functional limitations and the need for mobility devices. A detailed description and explanation

of the tests was given to each subject's parents and they signed consent forms approved by the research committee of the Centre for Child Rehabilitation and Development at Assaf Harofeh Medical Centre. The physiotherapists treating the children in this study did not know what tests would be performed, thus there were no variations in stair-climbing activity before the climbing tests were given. The 10 children with CP had received neurodevelopmental therapy for an average of 5 years, twice per week for 45 min per session prior to being tested. They were tested again following a 4-month recess over the summer vacation and holidays, when structured therapy is not usually provided.

2.2. Stair-climbing test and equipment

The stair-climbing test was developed in order to circumvent two main problems in the measurement of functioning locomotion of children with CP: (a) the difficulty of simulating their individual walking pace on treadmills because of difficulty in responding to start and stop commands and (b) the difficulty in precise measurement of mechanical work while walking on a level surface because the center of gravity is then not elevated.

When climbing, the distance component of the work done (W) over a finite time period can be calculated from the vertical displacement of the body (m). The force applied is the body weight (kg) and the work is easily calculated as the product (kg m). The mechanical efficiency of stair-climbing in healthy subjects is between 20% and 30% [9] and is lower in children than adults [10]. Other specific mechanical factors, such as variations of velocity and the force exerted by the feet on the steps, extraneous movements of arms and torso or the horizontal component of the body's progression, will alter the resultant efficiency, but are not involved in the vertical body weight elevation and the calculated total external work [11].

The stair-climbing test only requires values for the body weight and the height of the steps, providing the posture is similar at the bottom and top of the stairs. During the test the number of ascents are counted in a given time interval (e.g., 5 min) and the number of descents can be ignored. The average $\dot{V}O_2$ is measured while climbing up and down the stairs during this time. The resting $\dot{V}O_2$ may also be measured and subtracted to obtain the net $\dot{V}O_2$ for the stair-climbing work.

Table 1

Mean (S.E.) for age, height and weight of normally developed subjects (ND) and children with CP, whose functional limitations are categorized

	ND; 5	CP; 10	CP categories		
			n	Type of CP	GMFCS
Age (year)	6.6 (0.3)	6.3 (0.4)	3	Spastic diplegia	II
Weight (kg)	28.2 (3.3)	22.4 (2.4)	4	Spastic diplegia	III
			1	Athetosis	III
Height (cm)	124 (9)	112 (3)	2	Spastic quadriplegia	IV

Gross Motor Function Classification System (GMFCS) by Palisano et al. [8].

2.2.1. Stairs

A set of stairs was built that included four steps, each with a uniform height of 15 cm, a width of 62 cm and a depth of 27 cm and an upper landing 75 cm long. A handrail was attached to the stairs on each side at a height of 87 cm.

2.2.2. Metabolic measuring device

A portable TEEM 100 system (Aerosport Inc., Ann Arbor, MI) was used. The subject breathed through a face-mask, fitted to their individual facial contours. The exhaled gas passed through a flow meter to measure expired volume. An analysis of mixed expired O₂ and CO₂ was performed by galvanic and infrared cells, respectively. The system was calibrated with a known gas mixture and also an automatic calibrator. The $\dot{V}O_2$ was computed from analysis of the exhaled gas composition and expired volume. Heart rate (HR) was monitored by means of a Polar pulsimeter attached to the chest. The $\dot{V}O_2$ and HR were measured continuously during the work periods.

2.3. Test protocol

The tests were carried out in an air-conditioned room at the children's school and each child was tested individually. The equipment included the stairs, a chair with a backrest, a table holding the metabolic system, portable computer and printer for data recording. The children with CP were brought to the room in wheelchairs in order to avoid fatigue. The ND children arrived walking independently. Each child was given a detailed explanation of the equipment. After a period of familiarization with the system and exploring and manipulating the gas collection mask and the computer, the ascent and descent of the stairs was practiced. The subject was then connected to the facemask and to the equipment in stages. When they felt comfortable wearing the mask, resting baseline measurements were made while they were sitting comfortably on the chair with backrest for 5 min while being told a story.

Subjects were instructed to walk up and down the stairs continuously at a pace that was comfortable for them. They then performed the stair-climbing task for 4–5 min while connected to the portable metabolic system and the pulsimeter. After ascending to the top step they turned and descended in a forward direction, always keeping their head turned toward the metabolic monitor. The CP subjects used the handrail for assistance. A count was kept of the number of times they climbed up the steps. If they stopped or slowed their rate significantly they were encouraged to continue at their own regular, steady pace. After the stair-climbing, they returned to the chair and rested.

2.4. Calculations

Work done per time (power) was calculated in watts (W) during the stair-climbing test as: body weight (kg) \times 0.6 m

(top step height) \times number of ascents \times 1/time (min) \times 1/6.12 (kpm/min).

The gross energy cost in W of the stair-climbing bout was calculated as: total O₂ uptake (l) \times 5 (kcal/l O₂) \times 427.85 (kg m/kcal) \times 1/time (min) \times 1/6.12 (kpm/min) [10].

Although it has been shown that the work of descending stairs is about 1/3 that of climbing stairs in normal subjects [12,13], this can be ignored when the goal is to determine differences in W, EC and ME between ND and CP or changes over time in CP.

The gross mechanical efficiency (ME_g) was calculated in percent as: (W/EC) \times 100. The net ME (ME_n) was also computed, subtracting the resting $\dot{V}O_2$ from EC. The average slope of $\Delta HR/\Delta \dot{V}O_2$ was computed from the 15 resting and average stair-climbing test values for the 5 ND and 10 CP subjects before recess from therapy (b). The mean (\pm S.E.) slope was 405 (81) beats/l. The energy cost was then calculated indirectly from the measured ΔHR and this slope constant for each subject and this ME_{hr} was compared with the other values for ME.

2.5. Statistics

Measured values were compared between ND and CP(b) by two-tailed *t*-test. Differences in values before (b) and after (a) the therapy recess in CP were tested by two-tailed paired *t*-test. The *r*-values by standard least squares regressions were computed for W, EC and ME values before and after the therapy recess to compare dispersion of the values. "Repeatability" was estimated for W and EC according to Bland and Altman [14]. Statistical significance was assumed at $P < 0.05$.

3. Results

The average of the stair-climbing test measurements (\pm S.E.) of the 5 ND children and the 10 children with CP, before (b) and after (a) the therapy recess, are shown in Table 2.

3.1. Comparison between ND and those with CP

In comparing the values between ND with CP before recess, the former ascended more than five times as many steps in 4 min as CP ascended in 5 min and the difference was highly significant. As a result of this and the 26% greater body weight of ND (Table 1), the total work done by ND was 8 times greater than for CP(b) and the difference very significant.

The gross $\dot{V}O_2$ of ND of 1.43 l for 4 min was not significantly higher than for CP(b) (1.16 over 5 min). Per time the value was significantly higher for N (0.36 l/min versus 0.24 l/min, $P = 0.05$). Therefore, the gross EC in W was also 50% higher for ND than for CP(b), with the difference being of the same borderline significance ($P = 0.05$). As a

Table 2

Mean (SE) of stair-climbing measurements in normally developed (ND) children and children with CP before (b) and after (a) a 4-month therapy recess

	<i>n</i>	Time (min)	Ascents (number)	Work (W)	$\dot{V}O_{2r}$ (ml/min kg)	$\dot{V}O_{2sc}$ (ml/min kg)	Gross energy cost (W)	MEg (%)	ME _n (%)	HR _r (b/min)	HR _w (b/min)	ME _h r (%)
ND	5	4.00 (0.00)	34.8 (2.7)***	23.2 (0.5)***	5.8 (0.6)	12.8 (1.5)	124.8 (17.4)*	20.1 (2.8)***	38.5 (7.0)***	101 (5)	157 (4)*	49.5 (3.3)***
CP(b)	10	4.90 (0.07)	6.4 (0.5)	2.9 (0.4)	6.0 (0.6)	10.7 (0.8)	83.3 (10.8)	3.5 (0.2)	9.8 (2.0)	101 (4)	133 (5)	11.0 (1.6)
CP(a)	10	4.98 (0.02)	7.7 (1.1)	3.9 (0.8)	4.7 (0.4)	9.1 (1.1)	76.0 (9.3)	5.2 (0.8)*	16.7 (4.5)	101 (4)	128 (5)	45.8 (23.1)

$\dot{V}O_{2r}$: resting O₂ uptake; $\dot{V}O_{2sc}$: total stair-climbing O₂ uptake; W: watts, for work and energy cost; MEg: gross mechanical efficiency; ME_n: net mechanical efficiency; ME_hr: mechanical efficiency predicting energy cost from HR.

* Significant difference from CP(b) noted by $P < 0.05$.

*** Significant difference from CP(b) noted by $P < 0.001$.

result of this EC difference and the 8 times higher W, the MEg was significantly higher for ND (20% versus 3.5%). The resting $\dot{V}O_2$ values between ND and CP(b) were not significantly different. Subtracting the resting $\dot{V}O_2$ values from the stair-climbing values, the MEn values were 10% and 38% for CP and ND, respectively, with a higher *P*-value, but still significantly different.

The resting HR was about the same for both groups, but during the stair-climbing the HR was significantly higher for ND than CP(b) by 18%. The values for ME calculated from work estimated from the HR increase during stair-climbing were higher than for MEn, but the relative difference between ND and CP was similar.

3.2. Effect of 4-month therapy recess in children with CP

The body weight of the 10 subjects with CP increased significantly by 2.4 kg over the 4 months. They also increased the number of stair ascents slightly, and these two factors served to increase work by 33% ($P < 0.10$). The stair-climbing $\dot{V}O_2$ was slightly lower after therapy recess and the resting $\dot{V}O_2$ was also lower. This reduced the total EC 9% after the therapy recess and because of the increase in W, the MEg was slightly, but significantly, increased from 3.5% to 5.2%. This improvement probably resulted mainly from maturation, but implies that a 4-month recess in these subjects did not result in deterioration of functional status. Although MEn and MEhr showed larger increases, these were not significantly different from zero because of greater variation. This observation was reflected in lower correlation coefficients observed in the 10 CP subjects between (b) and (a). The *r*-values for W and EC were +0.83 and +0.70, respectively ($P < 0.05$), and repeatability for each was acceptable as indicated by the mean difference not being significantly different from zero and falling within $2 \times$ S.E., the estimated sampling distribution of differences in the population [14]. For MEg the *r*-value was 0.55 ($P < 0.10$), but for MEn and MEhr they were only 0.20 and -0.23 , respectively.

4. Discussion

An important issue in the assessment of rehabilitation interventions is the comparative basis of the population tested. Functional motor tests related to age norms aid in diagnoses and identification of problems in development, but are not as definitive in the quantitative assessment of changes in motor function following rehabilitation [15]. This finding of a very significant difference in external work performed and especially in the mechanical efficiency between ND and CP potentially supports it as a useful, sensitive and convenient measurement.

The EC of external work during the stair-climbing test constitutes a comprehensive expression incorporating the components that influence mobility. These components include body and limb mass, range of joint movement, height

of step and the relationship between walking velocity and length of step and other specific kinetic characteristics [16]. The EC measurement therefore makes possible a global and objective assessment of the efficiency of mobility between individuals. Other measuring tools used for the assessment of neurodevelopmental therapy that measure individual variables such as muscle strength and tonus, range of movement or walking components, do not make possible an assessment of overall mobility [17]. Gage has pointed out that energy saving is one of the principles of normal mobility [18].

Because brain lesions and formation abnormalities in children with CP can alter many of these variables and neurodevelopmental therapy emphasizes improvement of all of these variables, the measurement of $\dot{V}O_2$ and EC can indicate subtle changes following neurodevelopmental therapy. The use of EC measurements has increased over the past decade in the assessment of rehabilitation intervention [19–21]. However, frequently an index derived from heart rate and walking velocity is still used because of the difficulty of treadmill testing in this population. Disadvantages of the use of this measure are realized, especially during the execution of light to moderate bodily activity [22]. Our mean estimates of EC from HR appeared to be reasonable, but since resting and exercise HR are dependent on variable cortical input, as well as metabolism, it did introduce appreciable scatter into the calculations of MEhr. Similarly, resting HR is also variable and difficult to attain in a limited time in children and contributes to the increased variability of MEhr.

Mechanical efficiency appears to be the most useful measurement obtained with the stair-climbing test. Other previous stair-climbing tests, such as the Harvard and Masters step tests are based on similar principles. These tests require the ability to cooperate and maintain of a relatively constant rhythm and speed during the test [23]. Therefore, they can use HR estimates because they can be performed in controlled fashion by normally functioning subjects who are being screened or having their physical fitness assessed. Tests that require constant rhythm and speed are not appropriate for populations of children with CP.

The most important question to be answered in a gait outcome study is whether the functional ability of the subject to ambulate is increased and that it can be performed with less effort after the intervention. Gait abnormalities in children with CP increase the metabolic energy cost. The accurate measurement of $\dot{V}O_2$ as the energy cost, with the subject walking at a self-selected speed, remains the standard against which other methods for measuring the ease of walking must be compared [7,18]. A treadmill is often used to conserve space and time, however, many children with CP are unable to walk on a treadmill [19]. In addition, treadmill walking has the disadvantage that the mechanical work done cannot be accurately determined. However, mechanical efficiency comparisons between children with CP and ND children have shown significant reductions in mechanical efficiency in children with CP while walking [3] and at maximum stable workloads on a cycle ergometer [4],

both not well-suited for these children. Many children with CP are able to ambulate with wheeled walkers or bilateral crutches. The majority of these children are able to climb stairs utilizing their hands for assistance. They may be assisted by having their hands held on the bars as long as they are not assisted in raising the body weight vertically. The step test is limited in utility to individuals who have appreciable leg and arm function, however, even children that are not functional walkers can perform this test. Further studies with this test are needed to quantify precise repeatability and validity in subject groups varying in age and dysfunction to determine the test's specific applicability.

5. Conclusions

The stair-climbing test appears to meet the requirements for the periodic measurement of ambulatory function in children with CP and it was carried out in the children's natural school environment without requiring a special laboratory. It also avoided the use of a HR-derived index, which introduces variability. The test indicates significantly lower mechanical efficiency in children with CP compared with normally developed children. With further development and testing in more subjects with CP, the stair-climbing test may serve as a standard test for periodically evaluating the ambulatory ability in children with CP.

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