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Prediction of mechanical efficiency from heart rate during stair-climbing in children with cerebral palsy

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Abstract

Measuring mechanical efficiency (ME) is potentially useful to assess motor performance in individuals with physical disabilities. The purpose of this study was to determine the accuracy of predicting ME from heart rate (HR) during a self-paced stair-climbing test in children with a range of motor abilities. The participants were 12 normally developed children (ND) and 24 with cerebral palsy (CP), ranging in age from 5 to 15 years (mean: 8 years). Five were at level II, 11 at level III and 8 at level IV according to the gross motor function classification system. ME was calculated as the ratio of external work to O_2 uptake ($\dot{V}O_2$ ml/min) measured or predicted from HR. The absolute values of $\dot{V}O_2$ and HR during stair-climbing were not significantly correlated. However, the correlation between values above resting (d$\dot{V}O_2$ and dHR) was significant ($r = 0.61$). Furthermore, when including body weight as a second variable the prediction of d$\dot{V}O_2$ was significantly improved ($r = 0.85$). This resulted in a high correlation ($r = 0.96$) between measured and predicted net ME (ME_{net}). Predicted ME_{net} for 25 stair-climbing tests repeated after an average of 6 months resulted in an r-value of 0.92 with predicted ME_{net} of the first test. This study demonstrates that ME_{net} during stair-climbing can be predicted in children with a broad range of motor abilities from dHR and may be a simple tool to help define developmental stages or evaluating intervention efficacy.

Keywords: Body weight; Cerebral palsy; Energy cost index; Net mechanical efficiency; Oxygen uptake

1. Introduction

Mechanical efficiency (ME) quantifies the energy expended to perform a measured amount of external work. Skilled motor performance is characterized by increased ME, as the task is performed with reduced energy expenditure [1,2]. Evidence suggests that humans use energy-minimizing gait, with models confirming that force pattern and step frequency adopted at different walking speeds are those that minimize the energy cost of locomotion [3,4]. ME is relatively constant over a wide range of workloads for normally developed children (ND) and adults. The ME for stair-climbing and uphill running ranges from 20% to 30% [5]. The vertical displacement of the body when walking or running on a horizontal surface can be measured by motion analysis and the translation of this displacement into external work is theoretically possible, but controversial [6–8] and particularly complicated for a mechanically impaired gait.

Typically developed individuals may perform a task inefficiently because of inexperience or improper training resulting in unnecessary or erratic movements and excessive displacement of the center of mass. The inefficient motor behavior of children with cerebral palsy (CP) reflects abnormal motor control and is characterized by abnormal posture and movement patterns related to impaired

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coordination and/or regulation of muscle tone. These result from constraints of spasticity, increased co-activation of agonist and antagonist muscles at joints and reduced range of motion [9–11].

A number of studies have demonstrated improved ME after training and motor learning, indicating that movement patterns become more efficient with practice and repetition [2,12]. This suggests that the measurement of ME of motor skills may be useful for evaluating intervention outcomes and assessing development stages and changes with motor learning and practice. It is possible to measure ME of children with mild CP on a cycle ergometer, but a large number of children cannot pedal despite being ambulatory [13]. However, a recently developed stair-climbing test shows promise for the measurement of ME during ambulatory tasks in children with CP [14]. This test demonstrated significantly lower ME in children with CP (2–5%) compared with ND children (near 20%). Climbing stairs is a functional and useful locomotor motor task for children and adults and differs mechanically from walking. The differences include an increase in the range of movement of the lower limb joints and more intense muscular activity, generating larger forces and moments, especially in the vertical direction [15]. The energy cost of stair-climbing is a comprehensive measure of the components influencing mobility. These components include body and limb mass, range of joint movement and step height. The ME measurement in stair-climbing can therefore be a global and objective estimate of the efficiency of mobility because it accurately incorporates work output.

The most accurate measurement of energy cost is the direct measurement of oxygen consumption ($\dot{V}O_2$). The disadvantages of direct $\dot{V}O_2$ measurements include the cumbersome nature of the testing process and high costs of data collection systems. Several indices have been developed to estimate energy cost and $\dot{V}O_2$ from heart rate (HR), with the assumption that linear relationships exist between HR and $\dot{V}O_2$ in individuals with motor disorders and in children with CP [16,17].

Our aim was to develop a simplified clinical version of the stair-climbing test that might be applicable in children's natural environments. The specific purpose of this study was to assess the accuracy of predicting ME from the HR increase during a self-paced stair-climbing test in children with a range of motor function abilities. The sample ranged from ND children to those with severe CP.

2. Methods

2.1. Participants

The study was approved by the Ethics Committee of Assaf Harofeh Medical Center, Tel Aviv University, Israel. The children with CP were recruited from outpatient rehabilitation clinics, while the control group (ND) participants were recruited from family members of the medical center staff. The procedures and aim of the study were explained prior to obtaining the parent's consent. Parents accompanied their children during the tests.

Table 1
Mean (S.D.) age and weight of study participants

	CP	ND
n	24	12
Gender (F/M)	7/26	2/10
Age (year)	8.5 (2.4)	8.2 (2.2)
Range	5–15	5–11
Weight (kg)	24.0 (8.2)	29.4 (8.6)
Range	14.0–47.0	20.5–47.0

Thirty-six children and teenagers participated; 12 were ND children and 24 were diagnosed with CP. There were no significant differences in age and weight between the groups (Table 1). The functional level of children with CP was classified according to the gross motor function classification system (GMFCS) for CP [18]. Five of the children were at level II, 11 at level III and 8 at level IV.

2.2. Stair-climbing test and equipment

When climbing stairs the work over a finite time period can be calculated from the vertical displacement of the body. The force applied is the body weight and the external work is the product of weight and vertical displacement. Other specific mechanical factors, such as variations of velocity and force exerted by the feet on the steps, extraneous movements of arms and torso or the horizontal component of the body's progression will increase the metabolic cost, but are not included in the calculated total external work [19]. The stair-climbing test only requires values for body weight and step height when the posture is similar at the bottom and top of the stairs. The number of ascents is counted in a measured time interval (e.g., 4 min) and the number of descents ignored.

2.2.1. Stairs

The dynamic stair trainer (DPE Medical, Shoeva, Israel) was used for measuring external work. It has 4 steps, adjustable from 1 to 17 cm, with adjustable handrails. The stair height was set according to each child's climbing ability during pre-test trials.

2.2.2. Metabolic measuring device

The K4b^2 (Cosmed, Rome, Italy) was used as a portable telemetric system to measure $\dot{V}O_2$ and heart rate on a breath-by-breath basis. The portable unit (0.5 kg) also measures ventilation, $\dot{V}CO_2$, end-tidal O_2 and CO_2 and calculates other metabolic variables. Calibrations of the flow turbine with a 3-liter syringe and the gas analyzers with two known gas mixtures were performed before each test.

2.3. Testing protocol

Each child was given a detailed explanation of the equipment and then practiced stair-climbing. Two trials served as a practice test for familiarization and for setting the height of the stairs. After a rest, baseline measurements were made while sitting on a chair with backrest for 5 min and being told a story. Children then walked up and down the stairs continuously for ≈4 min at a self-paced speed, using handrails for assistance if desired. After ascending to the top step they turned and descended in the opposite direction. Children with level IV GMFCS were assisted with locating hands on the handrails, but not with lifting their body to the next step.

2.4. Measurements, calculations and statistics

2.4.1. Measurements

During the 5-min resting period that preceded the stair-climbing task, the HR and $\dot{V}O_2$ were measured breath-by-breath and values subsequently averaged for the 3rd and 4th min. This time interval was chosen to minimize variations due to ‘‘settling down’’ while approaching a baseline resting level over the first 2 min and changes due to ‘‘anticipation’’ of the task during the 5th minute of rest. The stair-climbing was then performed for >4 min at a pace selected by the subject and the stopping time and number of ascents recorded. After the test, the breath-by-breath $\dot{V}O_2$ and HR during exercise were averaged for the 3rd and 4th min to represent a quasi steady state value during work by neglecting the first two minutes when the metabolic rate was increasing. The absolute $\dot{V}O_2$ and HR values during the task were initially utilized in the calculations, as well as the working minus resting values for $\dot{V}O_2$ ($d\dot{V}O_2$) and HR (dHR). The effect of the descents on HR and $\dot{V}O_2$ were ignored, with the assumption that HR and $\dot{V}O_2$ are equally affected and therefore their relationship is not altered. No fixed percentage (e.g., 33%) was added to the external work during ascent to account for the work during descent, as this only serves to systematically increase the calculated ME.

2.4.2. Calculations

The external work was calculated in joules (J).

$$\text{External work (J)} = \text{body mass (kg)} \times 9.81\ \text{m s}^{-2} \times \text{number of stair ascents} \times \text{stair height (m)} = \text{kg m}^2\ \text{s}^{-2} \qquad (1)$$

Energy cost for stair-climbing was calculated from $\dot{V}O_2$ (ml/min), taking the caloric equivalent of 5 kcal per liter of O_2 [20] and 4186 J = 1.0 kcal [5].

$$\text{Energy cost (J)} = \dot{V}O_2(\text{ml/min}) \times (\text{L}/1000\ \text{ml}) \times \text{work time (min)} \times 5\ \text{kcal/L} \times 4186\ \text{J/kcal} \qquad (2)$$

The net ME (ME_{net}), subtracting the resting metabolic cost from the working energy cost, was calculated as:

$$ME_{net} = 100 \times \frac{\text{external work}}{\text{energy cost}} \qquad (3)$$

For example: If work time = 4.02 min, stair height = 0.734 m, mass = 40.0 kg and number of ascents = 20, then external work = 40 × 9.81 × 20 × 0.734 = 5760 J. With $\dot{V}O_2$ during work = 725 ml/min and resting $\dot{V}O_2$ = 234 ml/min, the total energy cost = (725–234)/1000 × 4.02 × 5 × 4186 = 41,312 J, and ME_{net} = 100 × 5760/41,312 = 13.9%.

2.4.3. Statistics

Correlation coefficients were calculated from least squares linear regressions to determine the significance ($p < 0.05$) of relationships between two variables. Multiple regressions were also calculated for two independent variables. Significance of differences between slope values of regressions was calculated by *t*-test [21].

3. Results

For the initial 36 runs on 12 ND and 24 children with CP, the correlation between the absolute values of exercise HR and $\dot{V}O_2$, measured during the last 2 min of stair-climbing, was not significant ($r = +0.28$, $p = 0.10$). However, the correlation between the increase in HR from rest to exercise and the corresponding increase in $\dot{V}O_2$ was significant ($r = +0.61$, $p < 0.001$). Therefore only ME_{net} and not gross ME was employed in the subsequent calculations. Because body weight is a major determinant of $\dot{V}O_2$ at rest as well as the metabolic requirement and work performed, it was used as a second variable in predicting $\dot{V}O_2$ and $d\dot{V}O_2$ from HR and dHR, by multiple regressions. The measured versus predicted $\dot{V}O_2$ and $d\dot{V}O_2$ are shown in Fig. 1A and B, respectively. The correlations are considerably higher between $\dot{V}O_2$ and $d\dot{V}O_2$ values predicted from HR and wt by equations shown in Fig. 1A and B, with the latter correlation being higher ($r = +0.79$ and +0.85, respectively).

The relationship between the values for net mechanical efficiency (ME_{net}), as calculated from mechanical work during stair-climbing and the measured and predicted $d\dot{V}O_2$

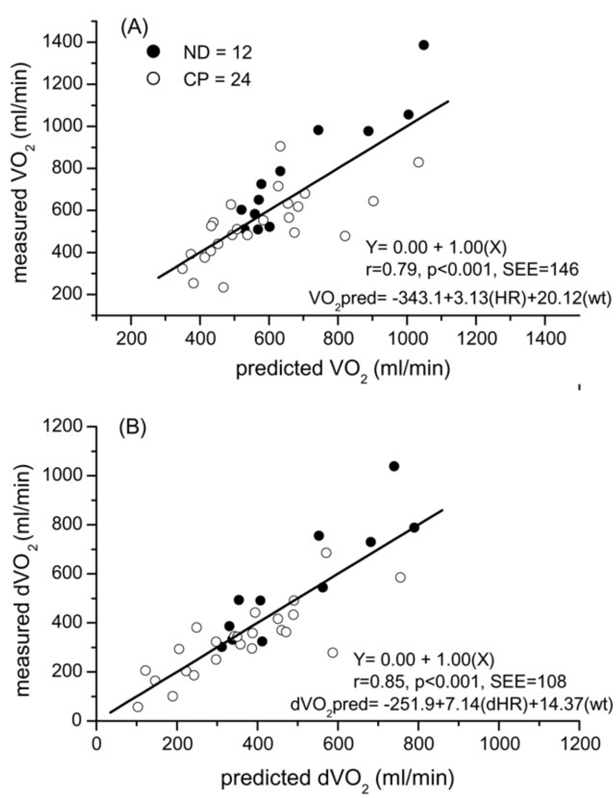

Fig. 1. Relationships between predicted and measured $\dot{V}O_2$ (A) and $d\dot{V}O_2$ (B). The SEE value of 108 ml/min in B is 11% of the range of measured $d\dot{V}O_2$ values.

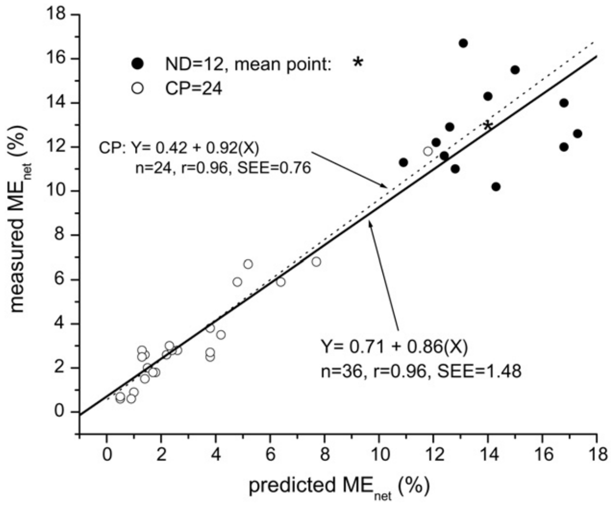

Fig. 2. Relationship between measured and predicted ME_{net} for all 36 subjects (solid line) and for the 24 children with CP (dotted line). The mean point for the 12 ND children predicted from the prediction equation in Fig. 1B for all subjects is indicated (*). The SEE for the 12 ND is greater than for the 24 children with CP, but the average S.D./mean for measured and predicted ME_{net} is 0.15 for ND vs. 0.82 for the children with CP.

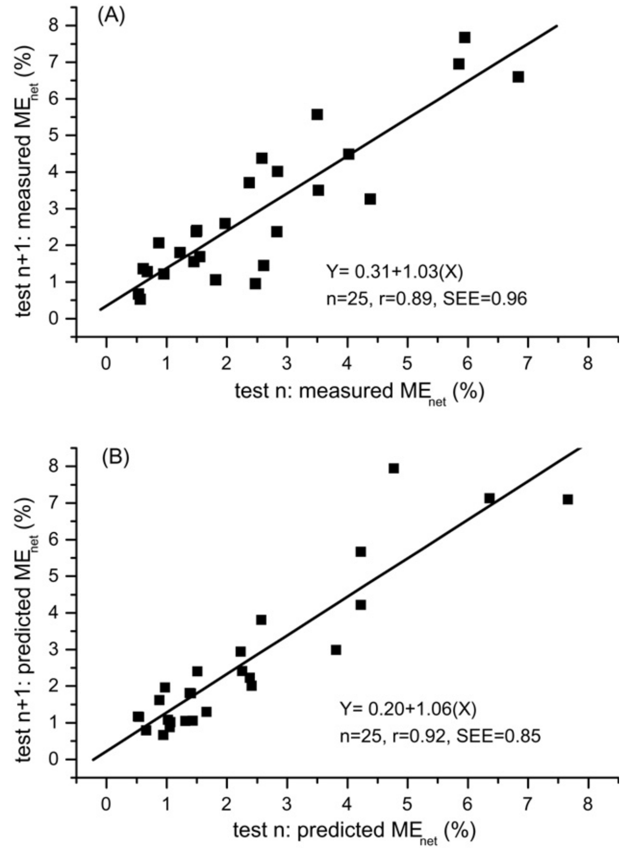

Fig. 3. Relationship between 25 repeated tests for measured ME_{net} values (A) and predicted ME_{net} values (B) in 16 children with CP. The graph depicts the results of consecutive tests, i.e., test 1 vs. 2 in nine, 2 vs. 3 in five and 3 vs. 4 in 2 children.

(shown in Fig. 1B) are presented in Fig. 2. As there was considerable overlap between values of the two groups of 12 and 24 in Fig. 1, all were combined to obtain the prediction in Fig. 2. This improves the prediction validity subsequently for children with CP having relatively mild motor dysfunction. The *r*-value is +0.96, with a slope value of 0.86. The slope for the 24 children with CP calculated separately was 0.93, not significantly different from 1.00.

In order to obtain an indication of repeatability, the stair-climbing test was repeated for some children with CP after an average time interval of 5.9 months. These 25 comparisons are shown in Fig. 3A for measured ME_{net} and in Fig. 3B for predicted ME_{net}. The slopes for both Fig. 3A and B regressions do not differ significantly from 1.00. The relationship between the average values of successive tests (X) versus the differences between them (Y = test $n+1$ minus test n) [22] did not show significant correlations for either plot ($p > 0.10$), indicating no systematic difference between repeated tests. The bias values were +0.4% and +0.3% ($p > 0.05$ versus zero) and SD of mean differences were 0.9 and 0.8 for Fig. 3A and B, respectively.

4. Discussion

The serial measurement of energy cost of a specific task to establish developmental stage, determine the efficacy of interventions and aid in prognosis has become an accepted tool in the rehabilitation of children and adults with movement disorders. Direct measurements of energy cost ($\dot{V}O_2$) are preferable, however, in a clinical environment this is often not practical. HR has been used to estimate energy cost, since a linear relationship exists for any individual between HR and $\dot{V}O_2$ during a ramp exercise or steady state exercises of varying intensity. The difficulties of utilizing HR lie in accurately modeling the relationship between HR and $\dot{V}O_2$ during the nonsteady states of exercise onset and in the different slope and intercept values of this linear relationship among individuals.

The use of HR indices, such as the energy cost index (ECI) [17] and physiological cost index (PCI) [16] for predicting energy expenditure during locomotion, has recently been reassessed. In adults, Hood et al. [23] obtained low correlations between $\dot{V}O_2$ and total heart beat cost index ($r = 0.15$) and PCI (0.14). Another study concluded that PCI reproducibility and its relationship to $\dot{V}O_2$ were only moderate [24] in children with CP. The validity of PCI as an outcome measure was also questioned by Boyd et al. [25] after a study in children and adults with physical disabilities. Keefer et al. [26] also re-evaluated the use of HR per walking speed for a group of hemiplegic children and found low correlations between this index and absolute and net $\dot{V}O_2$.

The HR indices that have been used in rehabilitation and clinical evaluations were usually determined from walking velocity or distance [17,27] on a horizontal surface. The relatively low work involved in this exercise may result in higher variability and lower repeatability of calculated indices. The stair-climbing activity in the present study allows subjects to perform substantial external work by repeatedly raising their whole body weight, in contrast to the more subtle sinusoidal oscillations of the center of gravity when walking on the level. Here the Newtonian definition of external work was used (N m) to express the product of force acting through a vertical distance and ME calculated according to classical exercise physiology definition as a percentage of mechanical work per energy expended by the body over a finite time. Although other studies have presented more sophisticated analyses of mechanical work and efficiency based on limb movements and anthropometric parameters while walking on force platforms [28,29], these gait analyses require special technologies and devices not applicable to routine clinical testing. Since body weight is a component of the external work done, as well as one of the factors determining the $\dot{V}O_2$ during exercise, the prediction and repeatability of ME_{net} by this stair-climbing test is higher when body weight is included in the prediction equation. Hiilloskorpi et al. [30] evaluated the relationship between HR and $\dot{V}O_2$ to estimate energy expenditure in adults. They concluded that body weight should be used together with HR to predict energy expenditure during walking and cycling.

The present study demonstrated that the exercise HR above the resting value gave a superior prediction of exercise $\dot{V}O_2$ above the resting value than did the prediction of $\dot{V}O_2$ from absolute exercise HR. This indicates that the prediction of ME_{net} is preferable to the prediction of gross ME from our measurements. This is not surprising, as Hiilloskorpi et al. [31] also reported a more accurate energy expenditure prediction with dHR during low activity and maximal uphill walking in adults. The correlations and corresponding predictions of $\dot{V}O_2$ and ME_{net} from this study during stair-climbing appear to be an improvement to those previously utilized. This improvement probably resulted from the incorporation of the body weight as a second variable in predicting $d\dot{V}O_2$ and precisely calculating the external work.

In the present and two previous reports [14,32], we demonstrated that children with CP could climb stairs even at GMFCS level IV. All children with CP in our studies accomplished this 4-min test at a self-paced rate, during which their ME_{net} is probably the highest [33]. Jeng et al. found that ND and children with CP voluntarily adopt a frequency and movement pattern of walking that minimizes energy cost [34]. Jones and McLaughlin reported that ambulant CP children had difficulty in pedalling continuously on an ergometer [13]. The stair-climbing task overcomes this limitation of inducing external work by cycle ergometer.

In conclusion, this study demonstrated that $\dot{V}O_2$ above resting levels during stair-climbing can be reasonably predicted for CP and ND children from the corresponding increase in HR above rest. This prediction is improved by incorporating body weight. ME_{net} can be calculated with this predicted $\dot{V}O_2$ $(-252 + 7.14{\cdot}\text{dHR} + 14.37\ \text{wt})$ and measured external work and these values demonstrate adequate repeatability for utility as a whole-body serial measure of motor function.

Conflict of interest statement

None of the authors had any financial and personal relationships with other individuals or organizations that inappropriately influenced this study.

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