Oxygen Consumption Estimation vs. Normalized Concentric Energy in Diplegic Children

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***Abstract*-Energy expenditure is considered an essential tool for assessing functional ability. However in most motion analysis laboratories this is not routinely measured.When the goal of surgical treatment is to functionality or to make easier the task effort,energy assessment provides a unique and important tool. An energyconsumption index which can be highly correlated with metabolic energy expenditure is presented in this work.It would enable physicians and researchers to evaluate physical performance on an individual basis and to perform retrospective studies.Since by definition concentric contraction of muscles is power generating while eccentric contraction is power absorbing, this work is focused on the concentric (positive) power intervals. It is assumed that energy cost increases during pathological gait due to the high percentage of concentric contractions.Then, concentric areas of power generation in the kinetic power graphs of hip, knee and ankle in children with cerebral palsy were calculated and then normalized with respect to subject weight, thus obtaining the Normalized Concentric Energy (NCE) index.The concentric energy obtained from NCE calculation on kinetic datafrom42diplegicchildren with the metabolic energy expenditure (oxygen consumption)were analyzed and compared. Four regression models (linear, exponential, quadratic and cubic) were carried out and a model validation was performed. Thecubic regression model showed the best fit to dataset.**

Keywords-Kinetic Variables; Energy Index; Oxygen Consumption; Joint Power

I INTRODUCTION

Normal gait incorporates several mechanismsto minimize energy expenditure.It is generally acknowledged that children with cerebral palsy (CP) walk inefficiently; and that these inefficiencies, in turn, result in reductions in both endurance and speed.

Therefore, in children with impaired gait secondary to cerebral palsy, one of the maingoals of surgical intervention is to reduce energy consumption per unit of distance walked.Energy assessment provides a unique and important tool in the assessment of surgical outcome, as itprovides information related to endurance, fatigue and the ability to complete daily living activities the gait requires[1,2]. Previous authors[3]have includedenergy conservation as one of five attributes of normal gait and suggest that loss of energy conservation reflects alterationsin anyof the other four[4].

There exist various mechanisms the body uses to conserve energy including the excursion minimization of the center of mass, control of momentum, and active and passive transfers of energy between body segments.The energy generated by the body to accomplish metabolic activities such as walkingcan be determined by direct or indirect calorimetryor by mathematical modelsthatestimate the energy required for limb-segment movement during walking.

The basis of direct calorimetrydepends on the fact that all of the body's cellular processes result in the production of heat, which can be measured directly by placing the patient in an air-tight, thermally insulated chamber.Indirect calorimetry is based on the fact that all metabolic activities in the body depend on the utilization of oxygen.Oxygen utilization can be measured and is most often expressed by two indices: oxygen consumption and oxygen cost. Oxygen consumption is the rate of oxygen uptake normalized by body mass and is normally expressed in units of milliliters of oxygen per minute per kilogram of body weight (ml/kg-min). Oxygen Cost describes the amount of energy needed to walk a standard unit of distance normalized by body mass and is normally expressed in milliliters per kilogram per meter (ml/kg-meter).

The Physiologic Cost Index (PCI)[4,5] and Energy Expenditure Index(EEI) are other methodsfor estimating energyconsumptionthatdepend upon heart rate and speed[6,7,8]. However, the reliability of the Physiologic CostIndex as a measuring tool when dealing with treatment outcomes in patients with cerebral palsy is in doubt. Recent investigations have shown that it is somewhat unreliable when compared to other metabolic measurements[9].Energy Expenditure Index heart rate expressed per distance walked provides information on energy economyas oxygen uptake perdistancewalked does.Therefore the heart rate by the distance walked provides an easily, reliable measure and assessment of the degree of walking impairment.

There are two more primary mechanical estimations of energy. Both are based on data usuallyavailable through gait analysis. One is inverse dynamics and the other is the work-energy theorem[10]. Using the former method, the energy requirement of individual joints can be calculated; however the method underestimates the energy cost of walking, particularly in the assessment of pathologic gait[11]. The other method is based on mathematicalsegmental analysis;that is, the kinetic and potential energy exchange as measured by the work-energy theorem [12,13,14].

Oxygen consumption and cost are usually the preferred energy expenditure measurement method, but it is not available at all gait labs since the equipment is rather expensive. Also, these analyses require to be carried out either before or after a gait analysis session, therefore an extra and significant amount of time and patient effort are required. This could affect the kinematics & kinetics recordings or distort oxygen consumption values (in case itwas done before) because patient could be tired and/or with pain(if he/she has a severe impairment condition). Therefore an estimation of oxygen expenditure done without requiringextra time or costscould be useful for gait analysis. The kinematics/kinetics recording would be very useful for clinical practical issues. Then, a method that uses the kinetic variables of gait analysis to estimate energy consumption comparedto metabolic energy estimation (oxygen consumption) is proposed and discussed in this work.

II MATERIALS AND METHODS

For this retrospective study, a group of forty-two (42) patients was chosen from the database of the Motion Analysis Laboratory of the Children's Orthopedic Hospital.The criteria for inclusion were as follows:

1) The child must have spastic diplegia ashis/herprimary diagnosis.

2) Energy consumption as well as kinematics and kinetics must be recorded at the same gait analysis session.

Patients did not use any walking aids. The hospital's laboratory-protocol enforces that patients must walk barefoot and without any aids such as split or walker when recording and processing kinetic data.

A. Recording Variables

Kinematics, kinetics and energy consumption records were obtained using the following procedure:

1) A clinical gait analysis was performed to each patient, according to Children's Orthopedic Hospital Motion Lab protocol.

2) Kinematics& kinetic records were taken using a Vicon 370acquisition system (Oxford Metrics LTD) that employedfive IR/60Hz cameras and 3 AMTI OR-6-1000 force plates (Advanced Mechanical Technologies, Inc.).

3) Energy consumption records were acquired with a COSMED K4b2 portable spirometer (Cosmed, Italy, www.cosmed.it). This equipment is able to simultaneously measure air temperature, flow, oxygen in air and CO_2.

4) Three clear right and left force plate steps, from a self-selected speed were recorded for each subject. The marker set suggested by Kadaba*et al.*[15]was used. A knee alignment device (KAD) for the knee axis computation was also used.

5) Energy consumption records included O_2 and CO_2 volume, breathing time, speed and distance with the following timing protocol: one-minute resting seated, one-minute resting standup, six-minute of exercise (walking, self-speed) and one-minute of seated final resting.

The same physical therapist performed the clinical evaluation, placed the markers and supervised the spirometer assessment. Data collection was done by a biomedical engineer.Clinical guidance, observation, and data interpretation were provided by the orthopedic staff of the laboratory.

The gait study included a bi-dimensional video, physical examination and biometric measurements of the patient, thenfollowed by a number of walking trials to obtainkinematics and kinetics.Finally, energy (oxygen) consumption acquisition was done as a separate procedure. Kinematics and kinetics were calculated for the three planes at all anatomical joint levels (ankle, knee, hip and pelvis).

Data plots were generated using Vicon Clinical Manager (VCM, Oxford Metrics LTD), which included gait consistency for each limb and leftversus right normal tracings. Raw data files also were available in C3D, VAD and TVD formats. Energy consumption and energy cost were then calculated using the average values obtained during the steady state period of the exercise phase.For each patient, the Normalized Concentric Energy (*NCE*) was calculated as follows:

$$NCE = \frac{1}{W} \sum_i \int_{a_i}^{b_i} p_i dt \quad (1)$$

Where$p$ is the net joint power of the hip, knee and ankleduring the intervals. In Equation(1), *NCE* represents the concentric energy for the i-th interval $[a_i,b_i]$ of positive power normalized by the patient's weight W(see Fig.1).

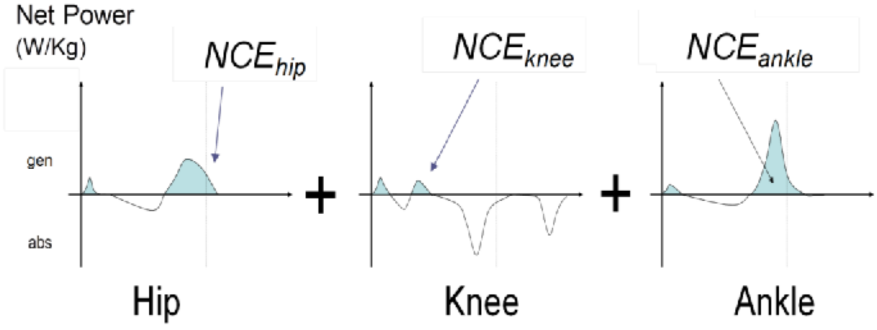

Fig. 1 An illustration of *NCE* calculation: shaded positive areabelow net power curve of a gait kinetics plot

B. RegressionModels

Since the energy used for comparisons is the total energy, it is necessary to sum the three *NCE*s, which were calculated at each joint level. File reading processes and *NCE* calculations were done withMatlab(MathSoft Inc.).

Finally, *NCE*, oxygen cost($CostO_2$) and consumption ($ConsO_2$) values for each patient were arranged for statistical analysis using four regression models: linear model (Eqn. 2), exponential model (Eqn. 3),quadraticmodel (Eqn. 4) and cubic model (Eqn. 5). Then, for oxygen consumption we can write:

$$ConsO_2 = m_2 NCE + b_2 \quad (2)$$

$$ConsO_2 = b_2\, m_2^{NCE} \quad (3)$$

$$ConsO_2 = k_2 NCE^2 + m_2 NCE + b_2 \quad (4)$$

$$ConsO_2 = c_2 NCE^3 + k_2 NCE^2 + m_2 NCE + b_2 \quad (5)$$

To validate the model, the dataset wasrandomly subdivided in two groups with half of the samples each one. Validation was based on the comparison of the fittings for both subgroups.

III RESULTS AND ANALYSIS

Oxygen consumption ($ConsO_2$) data were used for theregression models and some outsiders were removed. A total of 77 ConsO2-NCE samples were used for statistics.The resultsof r^2 for the minimum-square regressions using a floating free term are shown in Table I:

TABLE I MAIN PARAMETERS OF MINIMUM SQUAREFITTING

Parameter	Linear	Exponential	Quadratic	Cubic
r^2	0.7584	0.7131	0.8244	0.8332

And the fitting expression for each model is (Eqns. 6 to 9):

$$ConsO_2 = 0.5453\, NCE + 5.7004 \quad (6)$$

$$ConsO_2 = 7.4096 e^{0.0371\, NCE} \quad (7)$$

$$ConsO_2 = 0.0166\, NCE^2 + -0.0013\, NCE + 8.9504 \quad (8)$$

$$ConsO_2 = -0.007\, NCE^3 + 0.0493\, NCE^2 + 0.4114\, NCE + 10.033 \quad (9)$$

The data scattering and statistical fittings are shown in Fig. 2, where vertical axis is Oxygen Consumption (in ml/min/Kg) and horizontal axis is *NCE* (in Joule/Kg).

The slightly curved shape of the data cluster indicates that either partially-linear or non-linear models could be more suitable for such sample group. In a previous study[16] the authors analyzed a sample of less number of patients (30 children). The comparison with actual results is shown in Table II:

TABLE II COMPARISON OFR^2 VALUESBETWEEN 30 AND 42 PATIENTS

N:Number of Patients	Linear	Exponential	Quadratic	Cubic
N=30	0.5093	0.1527	0.6461	0.6533
Present N=42	0.7584	0.7131	0.8244	0.8332

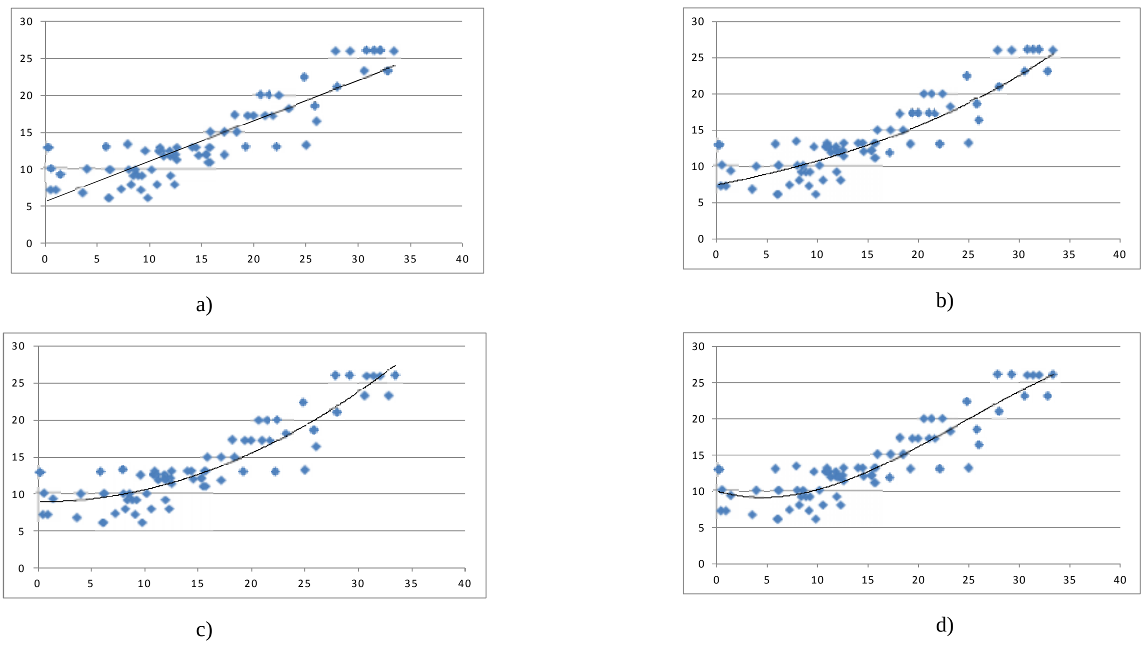

Fig. 2 Scatter plotsof Energy consumption (ConsO2) vs. concentric energy (*NCE*) for: a)linear, b) exponential, c) quadratic and d) cubicregression models

The coefficients of determination were above 0.70(p<<1 for allmodels), especially for the polynomial estimations (TableI)of quadratic and cubic models, showingar^2 greater than0.82. The best correlation is for the cubic model (r^2=0.8332), followed very closely by the quadratic model (r^2=0.8244). The poorest correlation was obtained with the exponential model (r^2=0.7131).Also, the cubic regression displayed the lowest random error variation.

Increasing the sample in around 30% (from 30 to 42 patients, TableII) raisesr^2 in more than 0.50 for exponential modeland almost 0.20 in the rest of them.Oxygen consumption vs. *NCE*outsiders were observed for low values of *NCE* (below 5 Joule/Kg).

Model Validation

Models were validated applying the fittings to two subgroups of randomly selected samples (N1=39, N2=38) of the dataset. Results of r^2 for the validation subgroups and previous methodology are shown in TableIII:

TABLE III RESULTS OF R^2 FOR MODEL VALIDATION SUBGROUP

Data Used *N*samples	**Linear**	**Exponential**	**Quadratic**	**Cubic**
Subgroup 1 N=39	0.7252	0.6664	0.8148	0.8231
Subgroup 2 N=38	0.7951	0.7651	0.8450	0.8501
Allsamples N=77	0.7584	0.7131	0.8244	0.8332

The behavior of r^2 for both subgroups is the same of the whole dataset (cubic model >quadratic model > linear model > exponential model), and Subgroup 2 showed greater values than Subgroup 1, and those for the whole dataset were always between Subgroup 1 and Subgroup 2 with less than 7% of difference (except for exponential fitting: r^2 for subgroup 1 = 0.6664). Plots of data scattering and fittings for both subgroups areshownin Fig.3 and Fig. 4,displaying very similar trends between subgroups even when compared with Fig.2 plots for the whole dataset.

Although in this work the relationship NCS vs. gait velocity is not reported, it must be said that the authors are working on this subject. Since gait velocity is related to the positive power in the kinetic graphs and the gait velocity is also related to the energy consumption, then the relation NCE vs. gait velocity will assess the relation between NCE and energy consumption, then NCE becoming a useful gait efficiency index.

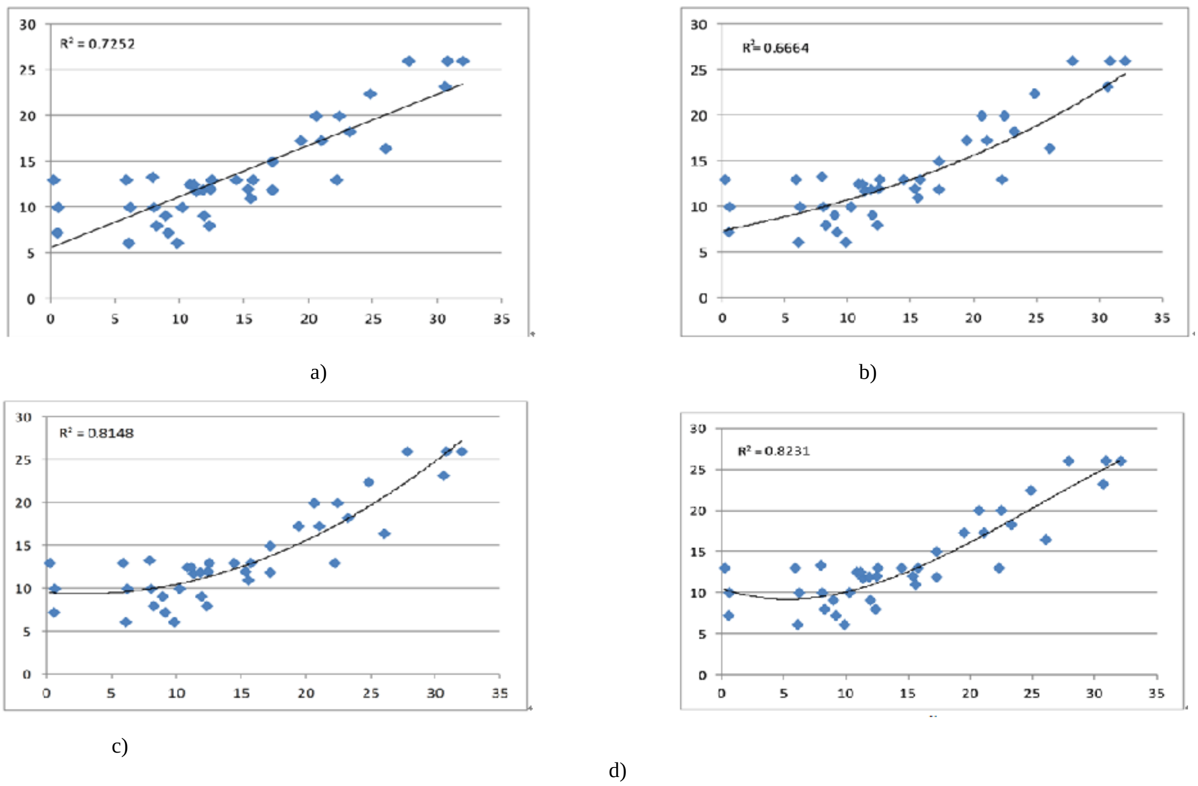

Fig. 3 Model validation: Subgroup 1 - scatter plots of Energy consumption (ConsO2) vs. concentric energy (*NCE*) - a) linear, b) exponential, c) quadratic and d) cubic regression models

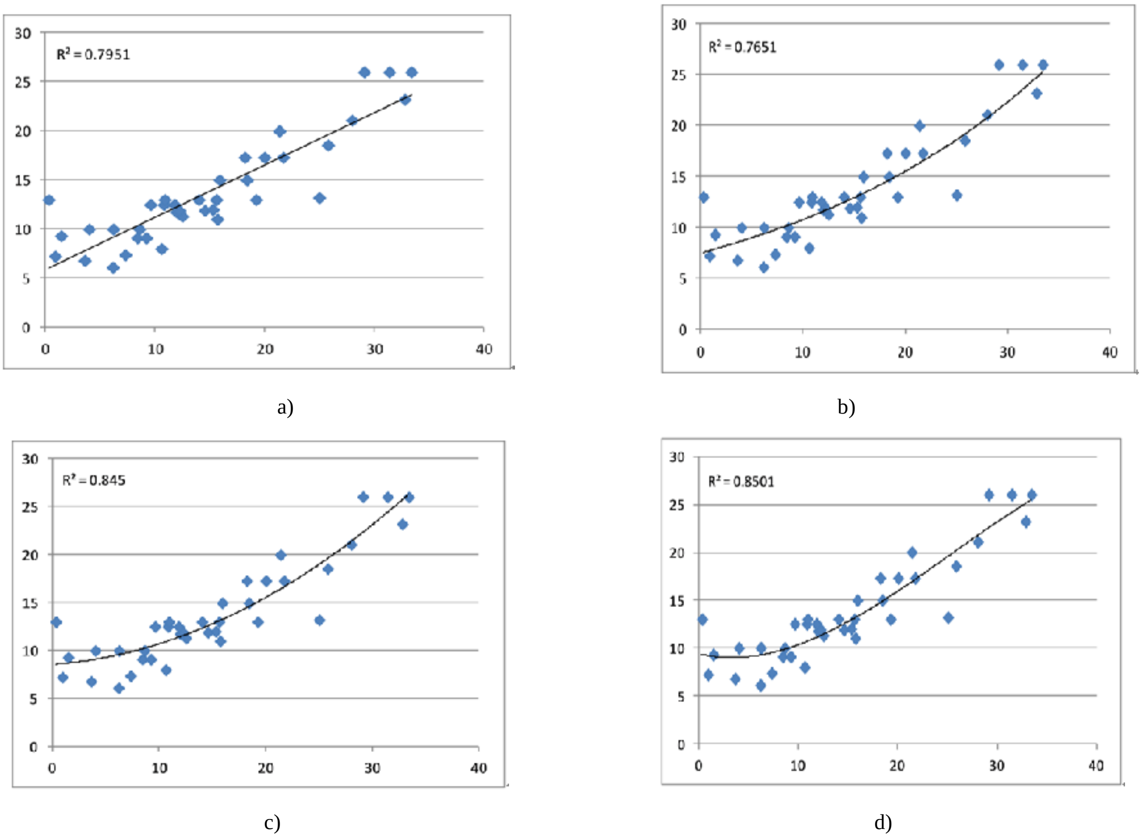

Fig. 4 Modelvalidation: Subgroup 2 - scatter plots of Energy consumption (ConsO2) vs. concentric energy (*NCE*) - a) linear, b) exponential, c) quadratic and d) cubic regression models

IV CONCLUSIONS

This research has suggested that a cubic polynomialexpressioncould be used in writing the relationship between energy (oxygen) consumption and *NCE*. However, the authors consider that the quadratic model should not be completely discarded.

When energy consumption is needed, *NCE* calculations would also reduce time and effort for the patient, since there is no need for a walk and/or six minute standing period, which is required for the exercise-based methods. As such, we believe that present results open an interesting research path in this direction.

The use of more patients in the current sample improved r^2 for all fittings. Then an increase of the number of patients is again strongly suggested in order to enhance statistics and to obtain big enough groups and then enabling the splitting of the sample according with age, sex, gait disorder, etc., for future studies. In previous works, age and sex were studied using this pathology, but the number of subjects used were still low to achieve reliable results.The model validation was done by applying the methodology proposed in this work to two subgroups of the dataset, obtaining the same results in all cases.

It is important in future work to consider eccentric energy and further analysis of hip power functions and gait cycle. In this research we assume that energy consumption increased in pathological gait, as a consequence of the increase in concentric contractions during it. An investigation oneccentric energy which is used not only for shock absorption, but also to harness the ground reaction forces for standing is being done.

The relationship between Concentric Energy and Metabolic Consumption is of great importance for the evaluation of patients with pathological gait, since the method would provide an estimationof the children’s physical endurance pre- or post-operatively, based only on the results of the kinematics analysis and kinetics.NCE could be part of the set ofinformationthatagaitanalysis report could include, and might be used as one of the features to analyze in the patient gait pattern. Also, this could allow gait laboratorieswhich do not have access to energy consumption technology to have an objective record of a patient’s physical endurance at low costs, and/or it enables them to use records which do not have oxygen consumption (older records for example).

An increase and categorization of data set and further studies in this relationship is currently being done.Also, other analytical models of one or more variables, with the hope of finding not only a function, but also an n-dimensional surface (or families of surfaces) as functions of other physiological parameters such as age, height, sex, heart rate, etc., even other gait parameters (space-temporal, kinematics, etc).

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