**Proceedings of the 28th IEEE**
**EMBS Annual International Conference**
**New York City, USA, Aug 30-Sept 3, 2006**



# Gait Energy Efficiency in Children with Cerebral Palsy

Sarah Rosen BS, Carole A Tucker PhD *Member, IEEE* and Samuel CK Lee PhD

*Abstract*— **Children with Cerebral Palsy (CP) expend up to three times the energy required for ambulation as compared to typically developed children of the same age. Measuring the metabolic energy required to execute a task is an intuitively appealing way to quantify task efficiency. Task energy demand is often quantified through pulmonary tests that measure oxygen consumption. Although providing an accepted measure of energy demand, these tests are technically demanding and staff intensive. For this reason, we sought a measure of gait efficiency based on spatiotemporal and kinematic parameters that would be reflective of the energy cost during ambulation in children with Cerebral Palsy. Gait data from 18 subjects with CP over 30 separate data collection sessions was used. Statistical analysis showed oxygen cost highly correlates to several kinematic variables, most notably, pelvic tilt, walking speed, landing angle and the biomechanical efficiency quotient (BEQ). The results of the work support the development of a computational model that would capture gait energy efficiency.**

## I. INTRODUCTION

Cerebral palsy (CP) is the most common neuromuscular disorder in children, affecting more than 1 in 500 children. Compared with 17 leading causes of congenital disorders, the total medical costs of cerebral palsy exceed all other diagnoses combined. Many therapies seek to improve walking efficiency in children diagnosed with cerebral palsy. Tendon transfers/lengthening/shortening, osteotomies, muscle strengthening, and the implantation of electrical stimulation systems all seek to alter gait mechanics so as to provide a more effective gait pattern. However, assessing the efficacy of such therapies can be difficult. Gait analyses are conducted both pre- and post-therapeutic interventions to quantify changes in gait biomechanics [1]. An assessment can then be made to determine whether individual gait parameters/profiles are more like those seen with typically developed children. Such analyses allow the clinician to quantify and compare specific mechanical aspects of walking efficiency. However, as there has been little work to define a simple, clinically feasible kinematic-based indicator of gait efficiency.

Measuring the metabolic energy required to execute a task is an intuitively appealing way to quantify task efficiency – lower energy requirements imply greater mechanical efficiency. Therapies that reduce the energy demand of a task are believed to be effective therapies. In the clinical setting, task energy demand is quantified through pulmonary tests that measure oxygen consumption during task execution. Although providing an accepted measure of energy demand, these tests are technically demanding, staff intensive and the encumbrance of the equipment alone may impact gait efficacy in children. For these reasons, we sought a gait measure based on biomechanical parameters that are related to the energy cost of ambulation and are sufficiently sensitive to evaluate the relative metabolic efficiency among our population of patients with cerebral palsy. Such a measure would assist in the evaluation of the effectiveness of different therapies on improving metabolic efficiency of ambulation [2,3,4,5].

One resultant effect of the kinematic determinants of gait is to reduce the vertical displacement of the center of mass so as to diminish the energy cost of walking. Thus, Kerrigan et al. [6,7] posited that a measure based on the vertical displacement of the sacrum could be a clinical means to assess biomechanical performance during walking. Because the sacrum provides a reasonable estimate for the position of the body's center of mass [8] vertical sacral displacement could approximate changes in potential energy associated with gait and the kinetic energy used to create such changes in potential energy. Kerrigan defined the Biomechanical Efficiency Quotient (BEQ) as the average sacral displacement from a measured predicted height predetermined and calculated from the static, standing sacral height and average stride length of the individual. Gait strategies that yield a higher BEQ measure are posited to be more energy intensive and less efficient. The effectiveness of interventions could be reflected in a lower BEQ indicating a more energy efficient gait pattern.

In developing the BEQ, Kerrigan et al. first demonstrated a significant linear correlation between average vertical displacement of the sacrum and oxygen consumption in healthy adults [6]. Subsequently, they applied the BEQ to walking trials of 20 patients with various neurological-based gait disabilities walking both with and without ankle-foot orthoses (AFOs). The patients subjectively reported that walking was easier with AFO use and in all cases the BEQ measure for walking trials with AFO use was less than that for trials without the AFOs [7]. These findings support the contention that the BEQ may be able to discriminate between levels of efficiency and thus

Manuscript submitted April 24, 2006. This work was supported in part by Dr. Samuel CK Lee's NIH R01 HD043859 and Shriners Grants 8350, 8510 and 8520.
C. Tucker is Director of the Motion Analysis Laboratory and research scientist at Shriners Hospital for Children– Philadelphia and an Adjunct Professor in the School of Biomedical Engineering, Drexel University, Philadelphia PA. Contact: Shriners Hospital for Children – Philadelphia,3551 North Broad St, Philadelphia PA 19140 (email: ctucker@shrinenet.org ).
S. Rosen is a doctoral student in the Biomedical Engineering Program at Drexel University, Philadelphia PA, USA (email: sr952@drexel.edu ).

may be able to assess the effectiveness of different types of interventions.

Other parameters of gait can also be considered when assessing gait efficiency. Fonseca et al. [9] studied the gait of children with spastic hemiplegic CP and modeled the affected leg of children with spastic hemiplegic CP as a spring. The stiffness characteristics of the spring represents the ability of these children to raise the center of mass on the non-affected lower extremity to effect an increase in the amount of potential energy transferred to the elastic energy on the affected side and thus lowering the kinetic to potential energy ratio of the center of mass during ambulation. Their findings showed that the affected lower extremity has less vertical stiffness at slow speeds, a smaller kinetic to potential energy ratio as well as a smaller landing angle in most speeds of walking when compared to their non-affected side or typically developing children of the same age.

Donelan, Kuo et al. [10,11] developed a walking model that can predict metabolic cost in which they used a simple pendulum motion with pendular arc motion to describe the step-to-step transition and the work required to redirect the center of mass (COM). In the model positive work was defined as work performed by the trailing leg just before or simultaneous with negative work performed by the leading leg. Their findings showed that work and metabolic energy expenditure increase approximately with the fourth power of step length and the second power of step width. The model shows that step-to-step transitions are significant in their direct contribution to energy expenditure in healthy human adult subjects.

Given the complex nature of ambulation in children with cerebral palsy, it is likely that singular approaches to model or predict gait energy efficiency could fall short. We postulate that a model using additional kinematic data would provide a more accurate representation of energy efficiency than existing methods. In our model, called the gait energy efficiency computation model (GEE), we also prioritized the desire to use kinematic variables that can be measured across children with different ambulation capabilities in clinical settings.

In this abstract we describe the foundation work to date in the development of our GEE model. This work is based on previous literature and our retrospective study.

The primary purpose of this pilot study was to identify parameters that: 1) provide a more accurate representation of gait energy efficiency, 2) provide the basis for a computational mechanical model of gait in children with CP and 3) parameters that are measurable using wearable sensor technology.

## II. METHODS

### A. Subjects

A convenience sample of 18 ambulatory children ranged from 7 to 13 years of age (Mean=10.14 SD=2.11), 8 males and 10 females, with spastic cerebral palsy (bilateral lower extremity involvement) who underwent both gait analysis and energy expenditure testing in our motion analysis laboratory were used in this analysis.
The analysis included 30 data collection sessions, with some children having more than one data session collected at different points in time.

### B. Procedures

Energy expenditure during steady state walking was assessed via gas dilution method utilizing a SensorMedics® VMax metabolic cart and software. Each child wore a mask attached by a hose to the metabolic cart during the test. The volume of oxygen per kilogram (VO2/kg) used every minute was measured and calculated. Each subject sat quietly at the beginning of the test for a minimum of 5 minutes to establish 5 steady state baseline values for energy expenditure (VO2/kg/min). At the end of the 5 minutes, the subject stood up and commenced a 2-minute warm-up period by walking barefoot around a 24-meter oval track at his or her self-selected walking speed. Following the warm-up period, the subject completed a minimum of 5 minutes of walking until steady state values of energy expenditure were obtained. One investigator manipulated the sampling hose during the walking portion of the test to allow unobstructed walking around the track. The distance traveled per minute was recorded, as the subject walked. Once steady state values during walking were achieved, the subject entered the recovery phase and sat quietly for 5 minutes.

Gait analysis was used to quantitatively assess spatiotemporal, kinematic and kinetic measures of gait for the GEE. The Motion Analysis Laboratory at Shriners Hospital –Philadelphia is equipped with a motion analysis system consisting of a 7-camera Vicon motion capture system (Vicon Motion systems, Lake Forest, CA); 4 AMTI force plates; and Motion Lab Systems MA-310 surface EMG recording system (Baton Rouge LA).

All subjects were evaluated using a standard clinical motion analysis protocol, which includes a clinical examination by a physical therapist, video observation and 3-D motion analysis. Each subject wore shorts and a T-shirt throughout the evaluation and gait analysis was performed with the subject barefoot.

Reflective surface markers were placed on the subject prior to the test in accordance to the laboratory's standard gait analysis marker set. Kinematic data was collected from the pelvis, thighs, legs and feet of the subject. A standing calibration trial was used to establish joint center relationships [12]. Each subject walked at his/her freely chosen walking speed along an 8.4-meter level walkway. Video, force and EMG data were collected when the subject traversed the middle 5 meters. The motion analysis software also calculated spatiotemporal and kinematic data. Selected spatiotemporal and kinematic data were used for data analysis as described below.

### C. *Measures*

Selected spatiotemporal and kinematic data were analyzed including BEQ, knee angle, knee stiffness, landing angle, as well as other clinically significant kinematic gait variables and parameters based on the mechanical walking models developed by Donelan &Kuo [10,11] and Fonseca & Holt [11] as described below.

All of the kinematic variables were calculated in the sagittal plane, which is the plane of progression during ambulation. Landing angle was calculated according to Fonseca, and is reported as the angle between a vector connecting the center of mass to the ankle joint and another vector representing the vertical. Landing stiffness was calculated as the change in landing angle acceleration over the landing angle.

## III. Data Analysis

Kinemtaic and spatiotemporal data from end trials were processed into .c3d files by the Vicon system software. A Matlab program (The Mathworks Inc. 6.5, Natick MD) was written and used to calculate all other gait variables for each step, including the BEQ, knee angle and knee stiffness, landing angle and landing stiffness and the parameters based on the Donelan and Kuo model [10,11].

The energy cost of walking was calculated for each child for each of the 5 minutes during steady state walking by subtracting the averaged baseline resting energy cost and dividing the new value by the distance in meters traveled during that minute. The values obtained for each minute during walking were averaged to obtain a normalized energy cost of walking value (energy cost is equal to the VO2/kg/minute divided by meters/minute).

Once all variables were calculated, the results were averaged, for each subject's side, left and right, for a total of 60 gait strides (left heel strike to left heel strike) of data sets. Statistical (Statistica 6.1, Tulsa OK) relationships between energy cost and the other gait variables were analyzed using Pearson product moment correlation coefficients with a significance criterion of alpha $\leq 0.05$. Based on the correlation results, a regression model was run on chosen variables with oxygen cost as the dependent variable [13].

## IV. RESULTS

The results from the correlation analysis of 60 gait strides are presented in Table 1. The highest correlation between oxygen cost was with pelvic tilt which represents the angle from the horizontal line to the pelvic anteroposterior axis in the sagittal plane. Significant correlations, however, were also found for walking speed (r=0.64), landing angle (r=0.63) and BEQ (r=0.59).

TABLE I
SIGNIFICANT CORRELATION RESULTS BETWEEN THE VARIABLES BELOW AND ENERGY COST

| Variable | r | Alpha | N |
|---|---|---|---|
| Pelvic Tilt | 0.73 | 0.00 | 51 |
| Walking Speed | 0.64 | 0.00 | 51 |
| Landing Angle | 0.63 | 0.00 | 60 |
| BEQ | 0.59 | 0.00 | 60 |
| Cadence | 0.55 | 0.02 | 51 |
| Step Length | 0.50 | 0.00 | 51 |
| Landing Stiffness at initial contact | 0.50 | 0.00 | 58 |
| Maximum Hip Flexion | 0.41 | 0.00 | 51 |
| Mean Knee Flexion at Stance | 0.40 | 0.00 | 51 |
| Knee angle at initial contact | 0.36 | 0.00 | 60 |
| Minimum Knee Flexion at Stance | 0.35 | 0.01 | 51 |
| Dorsiflexion at initial contact | 0.30 | 0.04 | 51 |

r= Pearson's correlation value.
Alpha= Significant criterion for the correlation coefficients.
N= The number of available strides for each measure.

Next, regression analysis was performed for those variables with significant correlation using a forward stepwise regression model. Mean values were substituted for missing values with energy cost as the dependent variable. The results of the regression analysis are presented in Table 2. Regression results suggest energy efficiency during ambulation can be assessed using a combination of BEQ, landing angle, landing stiffness as well as maximum hip flexion during a gait cycle and the mean value of knee flexion at stance. A prospective study is underway to validate these results.

TABLE II
REGRESSION RESULTS
DEPENDENT VARIABLE: OXYGEN COST, $R^2$=0.78

| Parameter | Beta | Std. Err. Of Beta | Alpha level |
|---|---|---|---|
| BEQ | 0.52 | 0.06 | 0.00 |
| Landing Angle | -0.39 | 0.07 | 0.00 |
| Landing Stiffness | 0.27 | 0.07 | 0.00 |
| Mean Knee Flexion at Stance | -0.23 | 0.07 | 0.04 |
| Maximum Hip Flexion | 0.13 | 0.06 | 0.00 |

Beta= Regression coefficient which help in the evaluation of the relative contribution of each predictor to the overall prediction of the dependent variable.
Alpha= Significant criterion for the regression coefficients.

## V. Conclusion

The results of this work provide insight into the relationship between mechanical and metabolic efficiency of gait in children with Cerebral Palsy. This work provides a conceptual basis for the development of improved computational models and monitoring devices that accurately assess the energy efficiency of gait in this population without the need for explicit measurement of metabolic expenditure. Such devices could utilize wearable sensor technology to measure kinematic variables. The computational model of gait energy efficiency can also be used to investigate the impact of clinical interventions to improve gait efficiency.


## ACKNOWLEDGMENT

C. Tucker and S. Rosen would like to thank their colleagues, past and present, in the Research Department and the Motion Analysis Laboratory at Shriner's Hospital for Children – Philadelphia. With particular thanks to Dr. Rami Seliktar, Ms Rosen's dissertation committee chair at Drexel University, Emily Slater, Carrie Stackhouse, Dr. Rich Lauer, and Dr. Patricia Shewokis for their additional insights and support.


## REFERENCES


[1] Gage JR. (2004) The Treatment of Gait Problems in Cerebral Palsy, First Edition. London: Mac Keith Press.
[2] Waters RL, Mulroy S. (1999) The Energy Expenditure of Normal and Pathological Gait. Gait and Posture 9(3): 207-231.
[3] Bowen TR, Lennon N, Castagno P, Miller F, Richards J. (1998) Variability of Energy-Consumption Measures in Children with Cerebral Palsy. Journal of Pediatric Orthopaedics. 18(6): 738-742.
[4] Boyd R, Fatone S, Rodda J, Olesch C, Starr R, et al. (1999) High- or Low- Technology Measurements of Energy Expenditure in Clinical Gait Analysis?. Developmental Medicine and Child Neurology. 41(10): 676-682.
[5] Rose J, Medeiros JM, Parker R. (1985) Energy Cost Index as an Estimate of Energy Eexpenditure of Cerebral-Palsied Children during Assisted Ambulation. Developmental Medicine and Child Neurology 27: 485-490.
[6] Kerrigan DC, Viramontes BE, Corcoran PJ, La Raia PJ. (1995) Measured versus Predicted Vertical Displacement of the Sacrum During Gait as a Tool to Measure Biomechanical Gait Performance. American Journal of Physical Medicine & Rehabilitation 74: 3-8.
[7] Kerrigan DC, Thirunarayan MA, Sheffler LR, Ribaudo TA, Corcoran PJ. (1996) A Tool to Assess Biomechanical Gait Efficiency: A Preliminary Study. American Journal of Physical Medicine & Rehabilitation 75(1): 3-8.
[8] Gard SA, Miff SC, Kuo AD. (2004) Comparison of Kinematic and Kinetic Methods for Computing the Vertical Motion of the Body Center of Mass during Walking. Docherty D. Human Movement Science 22(6): 597-610.
[9] Fonseca ST, Holt KG, Fetters L, Saltzman E. (2004) Dynamic Resources Used in Ambulation by Children With Spastic Hemiplegic Cerebral Palsy: Relationship to Kinematics, Energetics and Asymmetries. Physical Therapy 84(4): 344-358.
[10] Donelan MJ, Kram R, Kuo AD. (2002) Mechanical work for Step-to-Step Transitions is a major Determinant of the Metabolic Cost of Human Walking. The Journal of Experimental Biology 205(23): 3717-3727.
[11] Kuo AD, Donelan MJ, Ruina A. (2005) Energetic Consequences of Walking Like an Inverted Pendulum: Step- to-Step Transitions. Exercise and Sport Sciences Reviews 33(2): 88-97.
[12] Bell AL, Peterson DR, Brand RA. (1989) Prediction of Hip Joint Center Location from External Markers. Human Movement Science 8(1): 3-16.
[13] Lenth RV. (2001) Some Practical Guidelines for Effective Sample Size Determination. The American Statistician 55(3): 187-193.