ORIGINAL ARTICLE

Center of Mass Movement and Energy Transfer During Walking in Children With Cerebral Palsy

Bradford C. Bennett, PhD, Mark F. Abel, MD, Adam Wolovick, BS, Timothy Franklin, BS, Paul E. Allaire, PhD, D. Casey Kerrigan, MD

ABSTRACT. Bennett BC, Abel MF, Wolovick A, Franklin T, Allaire PE, Kerrigan DC. Center of mass movement and energy transfer during walking in children with cerebral palsy. Arch Phys Med Rehabil 2005;86:2189-94.

Objective: To gain insight into the mechanical inefficiencies of gait patterns used by children with spastic diplegia by analysis of center of mass (COM) movement and energy recovery.

Design: Prospective study using between-group measures to analyze differences between children with cerebral palsy (CP) and age-matched controls without CP.

Setting: Assessments were performed in a gait laboratory.

Participants: Fifteen children with spastic diplegia and 6 age-matched controls without CP with a mean age of 9.7 years.

Interventions: Not applicable.

Main Outcome Measures: Gait data assessed included temporal-distance factors, COM vertical excursion, work done on the COM, and the percentage of energy transferred and relative phase between the potential and kinetic energy.

Results: Children with CP had a 33% smaller energy recovery factor than the controls ($P<.001$). They also had 60% greater COM vertical excursion ($P<.02$) and a poorer phasic relation between potential and kinetic energies ($P<.02$), both of which contributed to greater mechanical work performed ($P<.003$).

Conclusions: Compared with the age-matched controls without CP, the children with CP were mechanically less efficient in their gait. Interventions that promote heel contact and roll over and greater knee stability to better utilize the kinetic energy of push-off could improve walking efficiency.

Key Words: Biomechanics; Cerebral palsy; Energy expenditure; Gait; Rehabilitation.

CHILDREN WITH CEREBRAL palsy (CP) typically expend 2 to 3 times as much energy in submaximal walking as age-matched controls without CP.[1] This increased energy use means that children with CP operate closer to their maximum level of effort and are prone to fatigue at low walking intensities.[2,3] Hence, reduced energy use while walking is an important goal of interventions. The metabolic cost of walking has been correlated with the mechanical work performed by children with CP,[4] but the different components of the mechanical work have not been investigated. We and others have observed the spring-like motion during the gait cycle of children with CP and hypothesized that this movement would be reflected in deviations of center of mass (COM) motion compared with able-bodied subjects. Thus, this research investigates the effectiveness of walking strategies in children with CP by analysis of COM mechanics and energetics.

The cause of the increased cost of walking in children with CP is important for clinical interventions. Unnithan et al[5] found a statistically significant correlation between the variability of metabolic energy cost and muscle cocontraction. However, almost 50% of the total variability of the metabolic cost was not accounted for by the cocontractions in the lower limbs. These investigators followed this work with a study of the correlation of metabolic cost to mechanical work performed,[4] in which they found that mechanical power measurements accounted for 87.2% of the total variability of the oxygen costs for children with CP when subjects walked at 3km/h on a treadmill. They did not examine COM mechanics. Olney et al[6] found increased mechanical energy walking cost in children with spastic hemiplegia and attributed this to poor energy exchange in certain segments. However, their 2-dimensional analysis did not attempt to examine the energy exchange of the COM or its components.

The pendular aspects of walking of both humans and animals have been noted for many years.[7] In an inverted pendulum conceptualization, minimization of work is achieved by the maximization of the recovery of mechanical energy (R). For R to be maximized, the potential energy (PE) and kinetic energy (KE) curves must be equal in amplitude and opposite (180°) in phase. Minimization of energy expenditure has long been considered a fundamental characteristic of walking. When permitted to walk freely, people choose a speed and stride frequency, which minimizes energy costs. Cavagna et al state that, "There is an optimal speed for walking in man at which the exchange between E_v (potential energy) and E_{kf} (kinetic energy) is maximal and both W_{ext} and W_{metab} (per kilometer) are minimal. The pendulum model is a good approximation of the mechanisms of walking at this optimal speed."[7(p260)]

This line of reasoning has led researchers to examine this mechanism of energy conservation in persons with walking disabilities. In their study of mechanical energies of children with hemiplegic CP using a 2-dimensional model, Olney reported that a "poor pattern of exchange between potential and kinetic energy of the HAT (head, arms, torso) segment contributed to high total energy costs."[6(p1354)] Researchers have also used COM analysis in studying patients with lower-limb amputations,[8] patients with gait disorders,[9] and those requiring total hip replacements.[10]

From the Departments of Orthopaedic Surgery (Bennett, Abel, Wolovick, Franklin, Allaire), and Physical Medicine and Rehabilitation (Kerrigan), University of Virginia, Charlottesville, VA.

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Reprint requests to Bradford C. Bennett, PhD, Kluge Children's Rehabilitation Center and Research Institute, Motion Analysis and Motor Performance Laboratory, 2270 Ivy Rd, Charlottesville, VA 22903, e-mail: *bcb3a@virginia.edu.*

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Table 1: Subject Biometrics and Preferred Walking Characteristics

Subjects	n	Age (y)	Leg Length (m)	Sex (M/F)	Walking Speed (m/s)	Stride Length (m)	Mass (kg)	Height (cm)	GMFM	Cadence (steps/min)
Patients	15	8.9±3.7	0.71±0.12	7/8	1.1±0.18	1.0±0.17	35±11	134±33	92±8	65±12
Controls	6	10.2±1.6	0.76±0.08	3/3	1.3±0.22	1.2±0.20	41±16	143±13	NA	55±16

NOTE. Values are mean ± standard deviation.
Abbreviations: F, female; M, male; NA, not applicable.

Work on the COM does not reflect the total effort of walking. However, the work required to move the COM has been found to be a significant portion of the total metabolic cost of walking. Duff-Raffaele et al[11] estimated that more than 50% of the metabolic energy expenditure at comfortable walking was used to lift the COM. More recently, Grabowski et al[12] came to the same conclusion using an innovative experiment in which they independently varied weight and mass during walking. Using a sophisticated numerical model of walking, Neptune et al concluded that "muscle energetic cost to raise the COM is significant and probably related to the metabolic cost of walking."[13(p824)] Thus a better understanding of the mechanics of the COM of children with CP should aid our understanding of their walking energetics.

Our hypothesis was that, compared with age-matched controls without CP, children with CP would have gait patterns that have greater vertical excursion of the COM and reduced energy transfer. Specifically, we hypothesized that the reduced energy transfer would be reflected in the relative phase of the potential energy to kinetic energy being further from 180° (the ideal value) compared with that of age-matched controls without CP. We also expected to identify periods in the gait cycle when energy transfer was particularly inefficient, as these might be the focus of clinical intervention.

METHODS

Participants and Procedures

Data were collected on a convenience sample of 15 children with spastic diplegic CP and 6 age-matched controls without CP. Subjects with CP were generally community ambulators, with a mean score of 92% on the Gross Motor Function Measure (GMFM)[14] and walked without aids. Subject anthropometrics are summarized in table 1. None of the subjects had undergone surgery or other significant treatments within the last 6 months. All tests were conducted in the Motion Analysis and Motor Performance Laboratory at the University of Virginia. Subject assent and parental consent was approved by the University of Virginia's Human Investigation Committee and was obtained for all subjects.

A full-body marker set of 38 markers was attached to the subjects after anthropometric measurements were taken. After a static trial, subjects walked at their self-selected speed and 3-dimensional kinematic data were collected using a 6-camera Vicon Motion Analysis System[a] at 120Hz. At least 3 trials were performed. The measurement volume of the Vicon System allowed the capture of 2 to 5 strides in each trial. Of the captured trials, the trial with the least velocity variation was analyzed and the average values for this trial were used in the data analysis.

Data Analysis

COM position was computed from the kinematic data with a model validated by Eames et al[15] written in the Bodybuilder computer language.[a] The model employed 13 segments and used the regression equations to define segment properties for children developed by Jensen.[16] Although it is clear that the anthropometrics of children with CP are different from age-matched controls without CP, analysis revealed the COM computations were insensitive to variations as large as those expected between adults and children. The model was further validated by comparison with forceplate computations of COM movement.

COM vertical excursion is a function of both leg length and step length. To allow comparison between subjects, COM vertical excursion for each trial was normalized by the vertical excursion of a compass gait model[17] with matching leg and step lengths. The compass gait model represents each lower limb as a single segment and assumes the COM follows the path of the hip joint, an arc with the radius of the leg length. Because knee and ankle joints are neglected in the compass model, the COM vertical excursion will be maximal.

The COM potential energy per unit mass was computed as:

$$PE_{com} = h \cdot g$$

where g is the acceleration due to gravity and h is the COM vertical location relative to its mean position during a trial. The kinetic energy per unit mass was computed as:

$$KE_{com} = 0.5 \cdot |v|^2$$

where $|v|$ is the magnitude of the velocity vector of the COM. The velocities were computed using a 3-point finite difference formulation applied to the position data. The kinetic energies were low-pass filtered with a bidirectional Butterworth with a 10-Hz cutoff frequency to remove noise from the differentiation process with zero-phase distortion. The amplitude ratio of PE to KE was computed from the average of the peak-to-peak values. We used a cross-spectral density function to calculate the continuous relative phase between the 2 energy components.[18]

Energy exchange was quantified by the method described by Winter.[19] The external work (W_{ext}) on the COM during N sample periods was computed as:

$$W_{ext} = \sum_{i=1}^{N} |\Delta PE + \Delta KE|$$

If one assumes no energy exchanges between KE and PE the work (W_{ne}) done by a segment during N sample periods is:

$$W_{ne} = \sum_{i=1}^{N} (|\Delta PE| + |\Delta KE|)$$

The energy recovery factor (R) represents the percentage of mechanical energy recovered via exchange between kinetic and potential energy in the COM movement. This is computed as:

$$R = 100 \cdot \frac{(W_{ne} - W_{ext})}{W_{ne}}$$

Table 2: Summary of Statistical Results

Parameters	Patients	Controls	*P*
W_{ext} ($J \cdot kg^{-1} \cdot m^{-1}$)	1.31	0.54	<.003
Normalized COM vertical excursion	0.8	0.51	<.02
Normalized COM lateral excursion	0.046	0.044	NS
PE/KE	2.15	1.3	<.003
R (%)	44	66	<.001
Relative phase (deg)	135	166	<.02

Abbreviation: NS, not significant.

If the PE and KE are in phase, with maxima and minima at the same time and the slopes of the 2 curves always having the same sign, then W_{ne} equals W_{ext} and there is no energy transfer, R equals 0.0. If energies are 180° out of phase with equal shapes and magnitude (ΔPE equals $-\Delta$KE), as in frictionless pendulum, W_{ext} equals 0 and 100% of the energy is recovered, R equals 100.

A harmonic analysis of both energy curves within each stride cycle was performed to assess the symmetry of the gait and assess the applicability of the inverted pendulum model for children with CP. The energy curves were detrended and normalized so the peak-to-peak amplitudes were one. The coefficients of the first 6 harmonics were estimated by fitting the data with the following Fourier series:

$$x(t)=a_0+\sum_{k=1}^{6} a_k \cos(2\Pi kft+\phi_k)$$

where a_0 is the mean position over the stride cycle; a_k and ϕ_k are the amplitude and phase of the kth harmonic, respectively; and f is the step frequency. Because there are 2 energy oscillations per stride, the terms with even k, which make equal contributions to each oscillation, reflect the symmetric aspects of COM movement and are referred to as intrinsic harmonics.[20] The term for k equals 2, the step frequency, is know as the fundamental intrinsic harmonic (FIH). Terms with odd k reflect asymmetries in the gait as they make unequal contributions to the oscillations and are called extrinsic harmonics. The term at k equals 1, the stride frequency, is known as the fundamental extrinsic harmonic (FEH). Between-group comparisons of the dependent measures were made with a 1-way analysis of variance using the software program Statistica 5.1.[b]

RESULTS

The results of this study supported our hypotheses and are summarized in table 2. The vertical excursion of the normalized COM was 80% of the compass gait model's excursion for the children with CP, but only 51% of this value in the control group. There was no difference in the lateral movement of the COM between controls and the group with CP. The children with CP had shorter strides but their preferred walking speed was not significantly slower because they had increased cadence, which compensated for the shorter strides. The ratio of the KE and PE peaks and relative phase of the group with CP were further from the ideal values of 1 and 180°. Furthermore, these parameters varied greatly in the group with CP and ranged from 1.5 to 3.2 for the PE/KE ratio and 65° to 171° for the relative phase of PE and KE curves with mean values of 2.15 and 135°; compared with 1.3 and 166° values measured in the controls.

The mean KE and PE curves are shown in figure 1. The reduction in the PE/KE ratio in the group with CP was due not only to the increase in COM vertical movement but also to a reduction in KE variation. Figure 2 plots the energy curves of representative individual trials showing periods of energy recovery. Energy recovery can occur only when the slopes of the energy curves have opposite signs and complete transfer can occur only when the slopes also have equal magnitudes. Typically, the patients with CP had a maximum in KE around the time of foot contact when the COM falls excessively compared with the controls. Analysis of the kinematic data revealed that, in the group with CP, on loading there is excessive ankle dorsiflexion and knee flexion, requiring additional energy to elevate the COM for foot clearance in mid to late stance. Also there is less KE available to transfer to PE to help in raising the COM. This walking pattern resulted in reduced energy recovery (R) and increased mechanical work per meter in the group with CP. In the controls, the heel

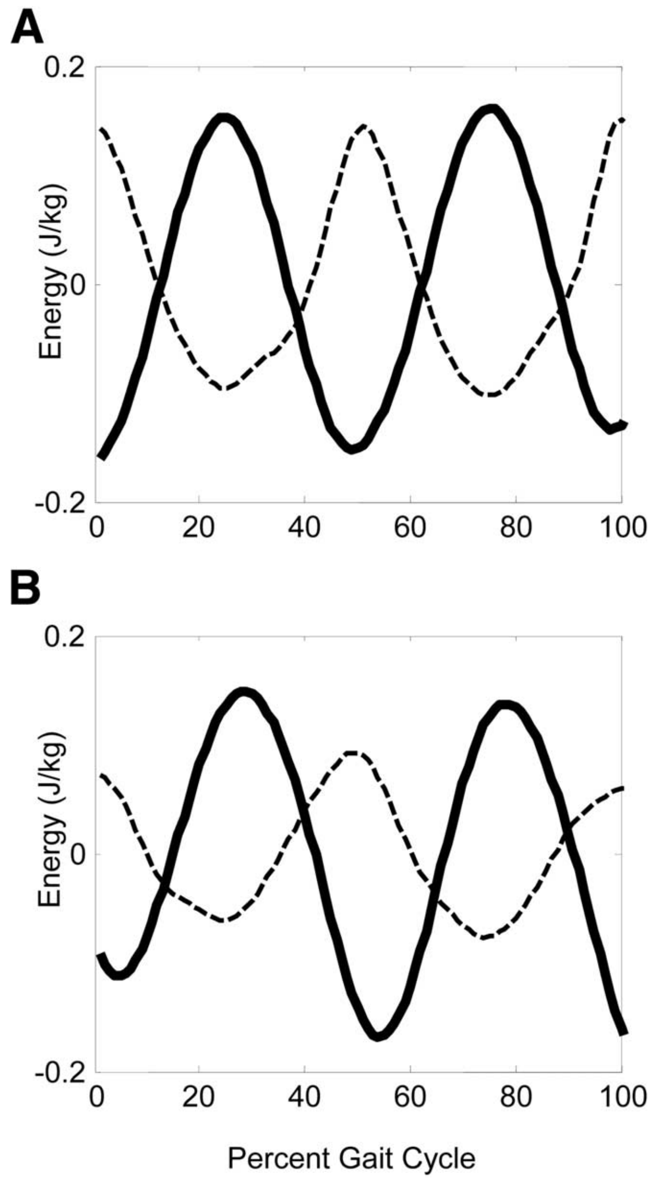

Fig 1. The mean PE (solid line) and KE (dashed line) variations about their respective means for (A) controls and (B) children with CP. The PE curves were very similar between the 2 groups. However, the KE curve of the children with CP was smaller in amplitude and lagged behind that of the controls by more than 25°. Both differences reduce energy recovery. The mismatch between values at 0% and 100% of the gait cycle reflect stride-to-stride variations.

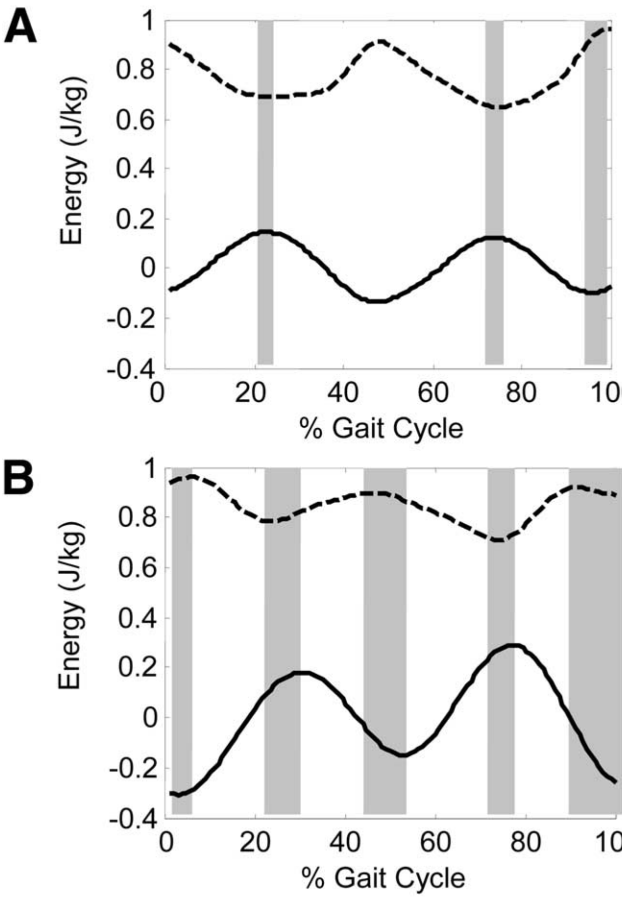

Fig 2. Plots of KE (dashed line) and PE (relative to mean COM position) for individual trials of (A) control subject and (B) patient with CP at similar velocities. Shaded areas are times when energy transfer cannot occur during walking cycle as PE and KE are moving in phase; with simultaneous increase or decrease in energies. Note that in the patient with CP, the PE variation (COM excursion) is greater while KE variation is less, and the energies are less symmetric than in the control. The patient with CP shows the often-displayed pattern of slowing down just before and after foot contact while COM is being lowered.

contact point acts as a pivot and the peak KE occurs closer to the minimum COM position, thus providing momentum to assist the elevation of the COM.

Figure 3 shows the amplitudes of the Fourier coefficients of the PE and KE curves. The results show that gait of the children with CP was less symmetric and energy curves were less like pure sinewaves than those of the controls. For both energy curves, the FIH (k=2) Fourier coefficient of the controls was significantly larger than that of the subjects with CP (P<.006). The asymmetry of the subjects with CP is most striking in the KE curves, where the k equals 1 coefficient was significantly larger (P<.02).

DISCUSSION

The results of this study support our hypothesis that the gait of children with CP is less pendular than that of the controls. An ideal pendulum has PE and KE curves that are equal in amplitude, 180° out of phase, and sinewaves. We found the COM energy curves of the group with CP lacking in all 3 measures. The increased vertical excursion of the group with CP meant that there was greater variation in PE than KE during the gait cycle. The lack of symmetry of the gait, the nonsinusoidal characteristics of the KE, and the relative phase between energy curves being further from 180° resulted in reduced energy recovery. However, it must be noted that the COM vertical excursion in the group with CP, although often differing between sides, was dominated by the FIH component of the curve. Thus it appears that the children with CP are using the same strategy as the controls, but are not able to execute it as well. The controls use the heel as a pivot at foot strike, conserving the momentum generated at push-off to propel the COM forward and up, whereas in the subjects with CP the COM falls as the strike point on the forefoot is followed by ankle and knee flexion. Furthermore, it seems that in midstance the group with CP must generate KE early to raise the COM to its peak. This event may be necessary for the patients with CP in order to clear the swinging foot because knee excursions are reduced in this group.[21] In other words, the children with CP performed more mechanical work per distance traveled to walk.

A simple numeric simulation can illustrate the relative importance of each of the factors affecting the recovery factor for the group with CP. Sinusoidal PE and KE curves 180° out of

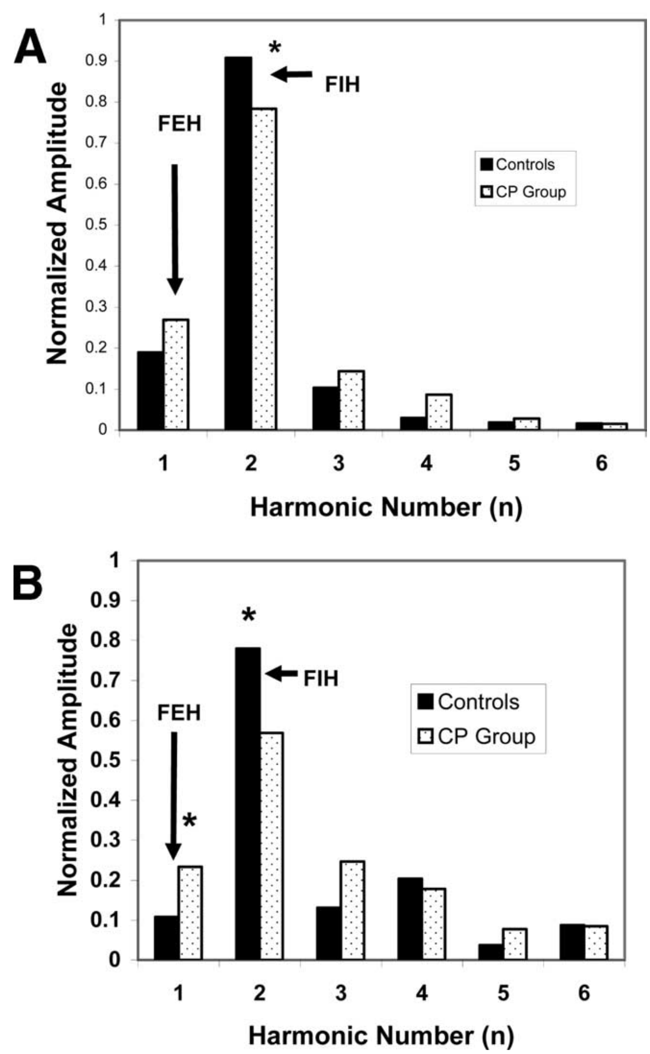

Fig 3. Fourier coefficients of (A) the PE and (B) the KE for children with CP and controls walking at their preferred speed. FIH and FEH are indicated. FIH differed between groups for both PE and KE. FEH differed between groups for KE. *P<.02.

phase with equal amplitudes have a recovery factor of 100%. If the phase is changed to 135° (the group with CP mean) leaving the amplitudes equal, the recovery factor is reduced to 62%. Alternatively, if the relative phase is 180° and the amplitude ratio changed to 2.15 (the group with CP mean), the recovery factor is 63%. If we change both the phase and amplitude ratio to the mean values measured in the experiments, 135° and 2.15, respectively, the recovery factor is reduced to 49%. Thus theoretically, changes in phasing or amplitudes can improve energy recovery by almost 50%. Our analysis suggests that one point for therapeutic intervention would be to promote heel contact and roll over and greater knee stability in order to make use of the KE of push-off more effectively. The effect of shape of the curves, the asymmetry, and higher order frequency components of the energy curves is small for the group with CP where the phasing is far from 180°.

This is the first full-body COM analysis of walking in children with spastic diplegia and age-matched controls without CP to explore the components of energy recovery, but some of the results are comparable to those of previous studies. The recovery factor of 66% at preferred walking speed in the control group is close to values reported in adults.[22-24] The small sample size of the control group was not deemed an issue because of the consistency of the results within the group and the overall agreement with published data. The recovery factor of 44% of this group of children with spastic diplegia is close to the recovery factor of 47% for energy transfers within the HAT reported by Olney et al[6] of children with hemiplegic CP. They concluded that "attention should be directed to restoring the sinusoidal pattern of motion . . . when energy costs are a therapeutic consideration."[6(p1354)] While we agree in principle with this statement, we believe our more in-depth analysis allows recommendations to be more specific; for example, a treatment to dampen the loading response and the subsequent fall of the COM that promotes a rolling function of the foot and ankle may allow more use of the KE.

In essence, the subjects with CP display some elements of pendular movement as a gait strategy but have less effective exchange between PE and KE perhaps due to a lack of a heel rocker, flexing at loading through the ankle and knee, and an ineffective second rocker caused by poor eccentric muscle control. Furthermore, the reduced KE relative to the controls reflects in part a disorder in magnitude and timing of power production. Reduced swing phase knee flexion in patients with CP may increase the demand for COM elevation to facilitate foot clearance.

If we assume that patients with CP optimize their walking based on their existing neuromuscular mechanisms, then we must be cautious when introducing treatments that alter peripheral aspects of movement. For example, therapeutic intervention such as passive ankle-foot orthotic bracing have the potential to restore a heel strike and first rocker but do little to address the defective eccentric control and may actually interfere with power production. An ideal interactive brace design would control limb alignment to facilitate a first rocker, free the ankle after loading to allow the forward momentum of the previous stride, and produce power as COM is transferred to the forefoot.

It is important to point out that our findings were from a group of patients with bilateral CP with relatively mild disability insofar as they could ambulate without hand-held aids. COM mechanics would clearly be different as the level of motor impairment and disability increased. We suspect that reduced KE would correlate with motor function deficit and that use of a walker may reduce the fall of the COM at loading and facilitate pendular movement over the forefoot.

CONCLUSIONS

This study has shown that the use of COM parameters provides insights that can aid kinematic analysis and can be applied to the gait patterns of an individual patient to either guide or evaluate interventions. The analysis can show when energy recovery is or is not possible and estimate the improvement in mechanical work resulting from a specific change in the gait pattern. Although each patient is unique, the COM dynamics in the subjects with CP showed significant deviations from normal, including greater vertical amplitude and longer periods in the gait cycle where there can be no exchange between PE and KE, especially during the loading and initiation of double support.

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