Locomotion in children with cerebral palsy: a review with special reference to the displacement of the center of mass and energy cost

Locomoção de crianças com paralisia cerebral: uma revisão de literatura, com especial referência ao deslocamento do centro de massa e custo energético

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ABSTRACT
The aim of the study was to review aspects of the displacement of the center of mass and energy cost of walking in children with cerebral palsy. The methodology used was a bibliographical review, whose articles had been chosen using the database PubMed and Google Scholar. There is unanimity from the studies that describe the locomotion of the hemiplegic children with increased vertical displacement of center of mass, inefficient exchange between kinetic and potential energy and elevated energy cost when compared with normal children. The mechanisms that explain these findings seem to have strong relation with the muscular co-contraction and the deformity in plantarflexion. Therefore, evaluation of the locomotion through cinematography and energy expenditure index is efficient to detect the effects of medical and therapeutic interventions.

KEYWORDS
Cerebral palsy - Hemiplegia - Gait.

RESUMO
O objetivo do estudo foi revisar aspectos relacionados ao deslocamento do centro de massa e gasto energético na caminhada de crianças hemiplégicas decorrentes da Paralisia Cerebral (PC). A metodologia empregada foi uma revisão bibliográfica, cujos artigos foram escolhidos utilizando a base de dados PubMed e Google Scholar. Há uma unanimidade entre os estudos, que descrevem a locomoção das crianças hemiplégicas com maior deslocamento vertical do centro de massa (CM), ineficiente troca entre energia cinética e potencial e maior gasto energético quando comparadas às crianças saudáveis. Os mecanismos que explicam esses achados não estão bem definidos, mas parecem ter forte relação com a co-contração muscular e a deformidade em

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flexão plantar presentes nos pacientes hemiplégicos. Portanto, meios de avaliação da locomoção como a cine-metria e índice de gasto energético são eficazes para acompanhar a trajetória dos resultados das intervenções terapêuticas.

PALAVRAS-CHAVE
Paralisia cerebral – Hemiplegia - Marcha.
INTRODUCTION

Gait is a basic requirement for daily activity and is known to be one of the most universal and complex of all human activities. It is a complex motor skill governed by several inter-linked pathways from the cortex to the muscles. However, impairment of gait is frequently responsible for long-term disability (Mauritz, 2002). Gait analysis of children with cerebral palsy (CP) or post-stroke adults has been used to study the basic biomechanics of their walking, which, in turn, has assisted in therapeutic and surgical decision making (Olney et al., 1987).

Cerebral palsy is a static encephalopathy that may be defined as a nonprogressive disorder of posture and movement, often associated with spasticity, muscle weakness, ataxia, rigidity, epilepsy and abnormalities of speech, vision and intellect, resulting from damage to the developing brain (Romkes & Brunner, 2007; Damiano et al., 2000). Hemiplegic CP is typically associated with single hemisphere injury and there is involvement of predominantly one body side with relative sparing of the contralateral limbs.

Thus, the CP is a condition that interferes in the acquisition of motor skills in infancy, which are essential to the performance of activities and tasks of daily routine. Specific abnormalities of gait are associated with variations in type and degree of CP's impairment. The involvement of upper motor neurons may result in neuromuscular disorders which include; hyperactivity of stretch reflexes, morphological changes of the tendons, muscles and connective tissue, muscle weakness and a decrease in the number of motor units (Burtner et al., 1999; Holt et al., 2000).

The most commonly observed characteristics of gait in children with spastic CP include limited hip and knee range of motion, excessive hip adduction and internal rotation, anterior pelvic tilt, pelvic obliquity, and persistent plantar flexion at the ankle. Common characteristics of CP gait include decreased heel strike, decreased walking speed, decreased stride length and/or cadence, and decreased ability to increase velocity on demand compared with adolescents without impairments (Aycicek; Akin, 2006).

During walking the body center of mass (CM) moves up and down, reaching a maximum during single limb support and a minimum during double limb support. For people with neuromuscular disorders such as stroke or CP, the CM vertical excursion may be increased (Russel et al., 2007).

The smoothness of the vertical body's CM displacement to minimize energy expenditure depends on several kinematic determinants: foot rockers, knee flexion wave in stance phase, knee flexion in swing phase, pelvic rotation, and pelvic list (Massaad et al., 2006).

The understanding of the alterations that occur to the musculoskeletal and physiological level in the walking have clinical implications for therapies aiming to improve walking economy in patients with gait disorders that affect CM motion and metabolic cost such as hip joint replacement, lower limb amputation, stroke, and CP (Ortega; Farley, 2005).

Minimization of energy expenditure has long been considered a fundamental characteristic of walking. This line of reasoning has led researchers to examine this mechanism of energy conservation in persons with walking disabilities (Bennet et al., 2005).

An essential question to the functionality in the locomotion relates to the total energy cost for this activity. Understanding how the modifications of the mechanics influence the energy cost of the locomotion assisting in the determination of the main parameters for the pathological gait.

Considering these assumptions, important in the process of rehabilitation of CP patients, this study aims at analyzing the movement of CM and energy cost in hemiplegics children, whose methodology consists of a bibliographical review using the database PubMed and Google Scholar in the period 1950 to 2008. The choice of this period for selection of articles is due the existence of classic items like Saunders et al. in 1953 entitled “The major determinants in normal and pathological gait” and articles about pendular mechanism of human walking by Cavagna and colleagues in 1963 and 1977. These articles are fundamental to understanding the current findings on the mechanics and energetics of locomotion.

LOCOMOTION AND MOVEMENT OF CENTER OF MASS

MECHANICAL MODEL OF THE INVERTED PENDULUM

The human locomotion is described as an alternate
movement of loss and recovery of balance with variation in the CM. When the person moves forward during stance phase, the CM body changes its position and causes imbalance of the body (CHAMBERS; SUTHERLAND, 2002).

Although the locomotion is the result of a complex series of actions which connect segments of the activation of the muscles engaging forces and producing torques transmitted through tendons generating the movement in various parts of the body, the human walk is characterized as a model capable of minimizing the expenditure of energy through the inverted pendulum, as figure 1.

![Figure 1. Mechanical model of human locomotion proposed by Cavagna et al., 1976: inverted pendulum for walking.](image)

The locomotion, analyzed by the behavior of the CM, suffers influence of three fundamental mechanical energies that are: gravitational potential energy ($E_p$), kinetic energy ($E_k$) and elastic energy (SAIBENE; MINETTI, 2003) demonstrated by the equations that follow:

$$E_p = mgh \quad \text{Eq. 1}$$

$$E_k = \frac{1}{2}mv^2 \quad \text{Eq. 2}$$

Where $m$ is mass (kg), $g$ is acceleration of gravity (9.8 ms$^{-2}$), $h$ is the vertical distance (meters), $v$ is speed of body CM (ms$^{-1}$).

In walking, potential energy ($E_p$) is high when the CM is on the point of body contact with the ground, while the potential gravitational energy begins to decline and horizontal kinetic energy ($E_k$) gets a gradual increase.

These patterns between horizontal kinetic energy and gravitational potential taking place in opposition of phase as described by CAVAGNA et al., (1963) and therefore with a process of reconversion between kinetic energy and gravitational potential (Recovery - R):

$$R(\%) = 100 \frac{W_f + W_v - W_{ext}}{W_f + W_v} \quad \text{Eq. 3}$$

where $W_f$ is forward work, $W_v$ is vertical work, and $W_{ext}$ is external work.

The recovery of energy quantifies the ability to store mechanical energy using the model of the pendulum. In an ideal pendulum the exchange of energy is complete. However, the maximum recovery of energy during walking is moderately high (about 60%) and it depends on the step length and the speed of walking (SAIBENE; MINETTI, 2003).

Recent literature suggests a contribution of elastic energy to the mechanisms of walking through the storage of energy and releasing in the Achilles tendon and possibly through the arch of the foot (ISHIKAWA et al., 2005), but the model inverted pendulum seems to be the main mechanism to minimize energy in walking (PEYRÉ-TARTARUGA, 2008, VANDERPOOL et al., 2008).

During each stage of walking, the potential gravitational energy and kinetic energy of CM range from a minimum to a maximum value. A priori, active movements of an organism are assumed to be powered by muscles: positive muscle work (concentric contraction) to increase potential energy and kinetic energy, and negative muscle work (eccentric contraction) to absorb potential energy and kinetic energy. Both positive and negative muscular work requires the expenditure of chemical energy. During walking, both the positive and the negative work actually done by the muscles to sustain the mechanical energy changes of the CM (positive and negative external work) are reduced by the pendular transduction from potential energy to kinetic energy and vice versa (CAVAGNA et al., 2002).

The mechanical cost of terrestrial locomotion is determined by ground reaction forces (GRF) in order to re-accelerate and move the body against gravitational force in a cycle of step. The method for analyzing work and mechanical external cost, using dynamometric
Platforms was introduced by Cavagna and colleagues (1963; 1964). Since then, the external work has been investigated in different conditions and populations (FORMENTI et al., 2005; FORMENTI; MINETTI, 2007; CAVAGNA et al., 1983; SCHEPENS et al., 1998).

The external work is commonly measured by the GRF, where potential and kinetic energy of the CM is calculated. The positive work performed by the muscles to move the CM during walking is also measured, determined by the sum of the positive increases of the curve of total mechanical energy of the CM (potential and kinetic) (WILLEMS et al., 1995; HECKE et al., 2007).

\[ E_{\text{ext}} = E_p + E_k \quad \text{Eq. 4} \]

where \( E_{\text{ext}} \) is total external work, \( E_p \) is potential energy, and \( E_k \) is kinetic energy (J.kg\(^{-1}\)).

\[ W_{\text{ext}} = \Delta E_{\text{ext}} \quad \text{Eq. 5} \]

where \( W_{\text{ext}} \) is external work, \( \Delta E_{\text{ext}} \) is variation of the positive increments of \( E_{\text{ext}} \) (J.kg\(^{-1}\). m\(^{-1}\)).

In contrast, the work necessary to accelerate the limbs with respect to the body CM during locomotion is a concept introduced by FENN (1930) and successively formalized as mechanical internal work (CAVAGNA; KANEKO, 1977). By summing the kinetic energy curves of single segments in a way to allow energy to transfer only among within-limb segments, and by summing all the energy increases in the resulting curves, internal work was calculated.

The mechanical internal work needed to accelerate the limbs with respect of the body CM, has been modeled by MINETTI (1998) as:

\[ W_{\text{int, theo}} = 0.1sf \bar{s} \left[ 1 + \left( \frac{d}{1-d} \right)^2 \right] \quad \text{Eq. 6} \]

where, \( sf \) is stride frequency (strides.s\(^{-1}\)), \( \bar{s} \) is average horizontal speed (m.s\(^{-1}\)) and \( d \) is duty factor (ratio of contact time and stride time).

The value of total work is obtained by adding the internal and external work, carried out by adding the curves of kinetic energy of the body segments and sum of the curves of potential and kinetic energy of the CM.

\[ W_{\text{tot}} = W_{\text{ext}} + W_{\text{int}} \quad \text{Eq. 7} \]

where \( W_{\text{tot}} \) is total mechanical work, \( W_{\text{ext}} \) is external work and \( W_{\text{int}} \) (J.kg\(^{-1}\). m\(^{-1}\)).

In an inverted pendulum conceptualization, minimization of work is achieved by the maximization of the recovery of mechanical energy. For recovery to be maximized, the potential energy and kinetic energy curves must be equal in amplitude and opposite (180°) in phase (BENNETT et al., 2005).

By the way, the recovery of energy during walking in children with CP is only two-thirds of that in typically developing children (AYCICEK; ISCAN, 2006; ORTEGA; FARLEY, 2005). Punctually it was possible to find that children with CP showed less recovery of energy, greater vertical displacement of CM; lower exchange between potential and kinetic energy contributing to the increase in mechanical work. It was also observed that children with CP walk with a shorter stride length and compensate with a higher stride frequency. Thus one may conclude that children with CP are mechanically less efficient in their walking, for adopting a less pendular locomotion (ORTEGA; FARLEY, 2005).

Some researchers hypothesized that minimizing vertical movements of the CM during walking would reduce the metabolic cost (SAUNDERS et al., 1953). However, an alternative view suggests that, minimizing the vertical motion of the CM during walking does not reduce the mechanical work required to move the CM and approximately double the metabolic cost (ORTEGA; FARLEY, 2005). Because vertical motion allows inverted pendulum energy exchange and reduces the mechanical work required to accelerate the CM in normal walking. Other factors probably contribute to the high metabolic cost of flat-trajectory walking, including greater muscle force generation to support body weight and greater positive muscle work performed to compensate co-contraction. Therefore maintaining normal levels of vertical CM motion and an extended stance limb are important factors to reduce the metabolic cost of walking.

MASSAAD et al. (2004) have demonstrated that the most crucial determinants optimizing the vertical CM displacement are the heel strike and the heel...
rise. In patients with CP, both these heel rocker movements are affected, which could partly explain the increase in this displacement. On the other hand, torsional deformities often observed in CP could interfere with the pelvic rotation, which is another potential determinant in smoothing the vertical CM displacement (CROCE et al., 2001). Raising the CM higher onto a plantar flexed foot would present some biomechanical advantages. In fact, the ankle loading torque is increased on a stiffer gastrocnemius–soleus muscle–tendon complex, which leads to a rebound in the manner of a pogo stick. Thus, higher vertical CM displacement could compensate for the lack of energy exchange of the CM by increasing the elastic potential storage (HOLT et al., 2000).

The decrease in forward CM displacement indicates a shorter step length that could be explained by a weak push-off, and/or an excessive deceleration of the leg in late swing due to the hyperactivity in knee flexors. In total, these ‘abnormal’ three-dimensional CM displacements may be a compensatory mechanism that allows individuals with CP to walk despite their impairments, and to do it in a way that minimizes metabolic costs. This interpretation would suggest that walking patterns adopted by individuals with CP might not be limitations but adaptations to the changed dynamics (FONSECA et al., 2001; HOLT et al., 2000, MASSAAD et al. 2004).

For some authors the most crucial gait determinant is the third foot rocker in association with heel rise, which explains up to 75% of the reduction in vertical CM displacement in normal gait (MASSAAD et al., 2006). Third foot rocker occurs when the plantar flexor muscles move the ankle from dorsiflexion into plantar flexion during push-off at the end of stance phase. This plantar flexion induces a relative elongation of the lower limb length, which raises the height of the CM when it has reached its lowest points of downward displacement, thus reducing the vertical CM displacement.

In children with CP, whatever the topographical types and levels of severity in motor involvement, they often show an equinus gait pattern with a deficient third foot rocker (i.e. a reduced ankle plantar-flexion range of motion in third foot rocker) and a reduction in plantar flexor power at push-off. Therefore, these children demonstrate 1.3 to 1.6 times greater vertical CM displacement than normal one.

**ENERGY COST OF LOCOMOTION**

In response to an inability of walking, a child with CP adapts using compensation to minimize the additional energy expenditure. The effectiveness and the penalties associated with this compensation depend, mainly on the severity of the inability and cardiovascular suitability of the patient (SAIBENE; MINETTI, 2003; WATERS; MULROY, 1999).

The metabolic cost of walking is determined by mechanical tasks such as generating force to support body weight, performing work to redirect and accelerate the center of mass from step to step, swinging the limbs, and maintaining stability (GRABOWSKI et al., 2005).

A variety of methods have been used by clinicians and researchers to assess the energy expenditure of movement in children with motor dysfunction (PICCININI et al., 2007; ROSE et al., 1990; GRABOWSKI et al., 2005). The quantification of the energy expended while walking can provide objective data in order to help evaluation of patients with walking disabilities and to help assess the effectiveness of therapeutic interventions, such as orthotics prescriptions, physical therapy or surgery. For this reason, energy expenditure can be considered a useful tool for assessment of functional ability, because its interpretation provides an indication of endurance, fatigue and ability to accomplish the routine daily task of locomotion.

It is known that children with CP typically expend 2 to 3 times as much energy in submaximal walking as age-matched controls without CP (BENNET et al., 2005; ROSE et al., 1990). 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.

Other researchers reported that a “poor pattern of exchange between potential and kinetic energy of the head, arms, torso segment contributed to high total energy costs” (OLNEY et al., 1987).

The study by JOHNSTON et al. (2004) compared the energy cost of walking in children with CP classified at different levels of the Gross Motor Function

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Classification System (GMFCS) with that in children with typical development. Children with CP displayed a higher energy cost of walking than the typically developing children. A strong correlation was found between the energy cost of walking and GMFCS level. This indicates increasing energy cost of walking with increasing severity of functional involvement. The reasons for the differences between the levels include the severity of the involvement of force, co-contraction, spasticity or inefficient transfers of energy between the segments of the body.

Children with CP have been shown to expend greater energy during walking when assessed by measuring either oxygen uptake or heart rate (HECKE et al., 2007; JOHNSTON et al. 2004).

The measurement of oxygen consumption can also be a method to quantify the efficiency of walking (BOWEN et al., 1998). Gait analysis allows the clinician to quantify specific mechanical aspects of walking; however, it cannot measure directly the overall efficiency of walking. Oxygen consumption (VO$_2$) during walking can be measured directly with an automated or non-automated system (KEEFER et al., 2004).

Drawbacks associated with the direct measurement of VO$_2$ include the cumbersome nature of the testing process and the high monetary cost required to purchase metabolic data collection systems. Consequently, indirect methods have also been employed to assess locomotion energy cost.

The energy expenditure index is an indirect method used to evaluate energy cost. It is obtained by subtracting the resting heart rate (HR) from the exercise HR and dividing the difference by the walking speed (WATERS; MULROY, 1999; KEEFER et al., 2004).

However, Keefer et al. (2004) suggest that the energy expenditure index to estimate the expenditure of energy in CP children walking should be applied with care. Findings from this study showed no relationship between energy expenditure index based on heart rate and gross VO$_2$ for different speeds in children with spastic hemiplegia.

On the other hand, researches carried out in order to ascertain whether the use of orthoses and/or surgical treatment would decrease energy expenditure in locomotion of children with CP showed that there is an improve in the rate of energy expenditure. That is, interventions that improve their poor biomechanics or increase aerobic capacity can make significant improvements in their walking efficiency (WATERS; MULROY, 1999).

PICCININI et al. (2007) also found high values for the rate of energy expenditure and oxygen cost in children with CP revealing to be as important parameters to characterize the cost of energy. The group affected by the CP walked with a lower velocity and higher oxygen cost that may be due to the presence of simultaneous contraction of agonist and antagonist muscle.

As in children with CP the study of MIAN et al. (2006) showed that the elderly without involvement of walking have a high metabolic cost of walking and a greater internal work accompanied by shorter steps and increasing in step frequency. The elderly have also increased muscle co-contraction that may be a strategy to improve articulate stability and explanation of the high metabolic cost of locomotion.

This research observed no substantial change in total mechanical work during walking in older adults, however recent observations suggest there is a reorganization of neuromuscular control with a decline in the relative contribution of ankle musculature for support and propulsion with a concomitant rise in the contribution of hip musculature.

The constitution of the muscles and tendons of the ankle allows an efficient production of work, however replacing the use of the structures of the ankle muscles of the hip may contribute to the metabolic cost of walking both in healthy elderly and in children with CP.

All the aforementioned studies indicate that muscle co-contraction of the lower limbs or spasticity during walking increases the expenditure of energy causing the displacement of the center of gravity to vary, leading to a less efficient pattern of walking. Changes to the transfer of energy between the segments also contribute to the increase in energy expenditure, and children with CP have atypical patterns of movement that may interfere in natural exchange or in the transfer of kinetic and potential energy between the body segments.

Muscle co-contraction can be defined as the simultaneous activation of agonist and antagonist muscle groups crossing the same joint and acting in the
same plane (DAMIANO et al., 2000). Mechanically, this activation pattern increases joint stiffness while limiting agonist force production. Despite its inherent inefficiency, co-contraction is a common motor control strategy primarily activated when a person needs increased joint stability or improved movement accuracy. But over-activation of the antagonist leads to a high metabolic cost, represented by the increase in oxygen consumption.

Increased co-contraction has been shown qualitatively during gait in children with CP. Although researchers have not yet precisely quantified co-contraction during movement in persons with CP, the degree of antagonistic coactivity has been estimated mathematically in this population using several different computational methods.

Possibly the electromyographic cost is an important tool to explain the energy of hemiplegics patients, adding important information to measures of external and internal work, widely discussed in this review.

Recently, a new hypothesis about the energy of the human walking, known as “electromyographic cost of human locomotion,” has offered new insights into the mechanisms that explain the mass-dependent metabolic expenditure necessary to go through determined distance (PEYRÉ-TARTARUGA, 2008).

The equine foot deformity is another factor strongly related to the high metabolic cost. This position of the ankle suggests a biomechanics adaptation that facilitates the use of dynamic resources available, because it provides a mechanism to transport the body CM in a model of mass spring, improving the ability to use a spastic triceps surae (HOLT et al., 2000).

This reinterpretation may have important effects for methods of rehabilitation. The lengthening of calcaneus tendon is frequently used to minimize plantar flexion, however, if it is an adaptation, the procedure for lengthening can have deleterious effects on the ability to walk, or at least it can change the gait pattern in no beneficial way.

Through the data presented in researches, it is possible to state that children with CP use strategies, not only from a biomechanical point of view but also in terms of energy expended during walking. They walk in low speed to keep the consumption of oxygen to a level close to normal.

**CONCLUSION**

In the classic model of the inverted pendulum that describes the human locomotion, the minimization of work is affected by the maximum recovery of mechanical energy, but the conversion of energy during walking in children with CP is smaller than the one found in normal children.

The main findings of the studies suggest that the locomotion of children with CP has a greater vertical displacement of CM, poor relationship of exchange between potential and kinetic energy, increasing of the mechanical work, less speed, smaller step length and increasing of the step frequency. In other words, children with CP are mechanically less efficient in their locomotion.

These children also have shown greater cost energy during walking than healthy children when assessed by measures of oxygen consumption and heart rate.

The co-contraction and equinus foot deformity are factors that are directly related to lower efficiency of movement of hemiplegics children.

One may conclude that energy expenditure index and cinematography help assess the walking of children affected by the CP. Through them it is possible to follow the trajectory of the results of therapeutic interventions and, thus, contribute to functional improvement of patients.

Among them there are some suggestions for future research in the area of human locomotion: implementing physical therapies interventions to tone’s inhibition and assessing changes in gait patterns, evaluating internal work between internal affected leg and not affected one, investigating the electromyographic cost of locomotion in patients with CP, exploring the pendular mechanisms to minimize energy into other levels of involvement of CP.
REFERÊNCIAS


