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Low gait efficiency is the primary reason for the increased metabolic demand during gait in children with cerebral palsy

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ABSTRACT

Children diagnosed with cerebral palsy (CP) use two to three times more metabolic energy to walk than their typically developing (TD) peers. The primary cause of the metabolic increase remains unknown. In this study, we analyzed metabolic energy, center of mass (COM) work, and gait efficiency for a large group of children diagnosed with diplegic CP in order to better understand the source of the excessive metabolic demand. Our primary hypothesis is that metabolic demand is increased in CP due to low efficiency conversion of metabolic energy into useful COM work. Results show that, on average, individuals with CP produce 27% more COM work, but have 99% higher metabolic demand than their TD peers. This causes individuals with CP to have a gait efficiency that is 31% lower than the gait efficiency of TD individuals. Therefore, low efficiency is responsible for nearly three quarters of the increase in metabolic demand. These results show that the high metabolic demands in CP are largely a result of low gait efficiency, not excessive COM work. Further work is needed to identify the specific neurological and biomechanical mechanisms underlying low gait efficiency in CP.

1. Introduction

As the most common childhood disability, cerebral palsy (CP) affects approximately 3.3 individuals per 1000 live births in the United States (Kirby et al., 2011). Children diagnosed with CP use two to three times more metabolic energy during walking than typically developing (TD) children (Bolster, Balemans, Brehm, Buizer, & Dallmeijer, 2017; Duffy, Hill, Cosgrove, Carry, & Graham, 1996; Norman, Bossman, Gardner, & Moen, 2004; Waters & Mulroy, 1999). Individuals with CP use the same amount of energy to walk as TD individuals use to climb stairs or run at a moderate pace (Harrell et al., 2005). These high metabolic demands have a significant impact on participation, activity, and quality of life.

To our knowledge, there are no treatments that exist to exclusively reduce metabolic demand for these individuals. Traditionally, interventions, such as the selective dorsal rhizotomy or orthopaedic surgery, have been used to reduce these high metabolic demands, but only as a secondary effect. The proposed metabolic demand reducing mechanism underlying these treatments is that the rhizotomy will reduce spasticity and co-contraction, orthopaedic surgery will correct skeletal malalignment, and as a result, metabolic demand will drop (Flett, 2003). However, while metabolic demand often drops following rhizotomy, it is not normalized (Trost, Schwartz, Krach, Dunn, & Novacheck, 2008). Even after subsequent orthopaedic surgery, metabolic demand is still excessive (Marconi, Hachez, Renders, Docquier, & Detrembleur, 2014; Thomas, Buckon, Piatt, Aiona, & Sussman, 2004). This indicates that the underlying origin of the high metabolic demand is not substantially affected by these procedures.

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The gait of individuals with CP is often referred to as being "inefficient", due to the high metabolic demands (i.e. metabolic consumption, metabolic power) measured during walking (Eagleton, Iams, McDowell, Morrison, & Evans, 2004; Kurz, Stuberg, & DeJong, 2010; Norman et al., 2004). In fact, poor gait economy, rather than gait efficiency, more appropriately describes this phenomenon. Economy is the *distance* that can be traveled from a given *energy supply*. Gait economy, then, can be defined as the overall distance that a person can walk from a given metabolic energy supply. Efficiency, on the other hand, is the amount of *useful energy* that can be derived from a given *energy supply*. Translating this concept of efficiency to analyze gait, we can define gait efficiency as the amount of energy that is used to do mechanical work on the body's center of mass (COM) from a given metabolic energy supply. From this definition, an individual with an inefficient gait would require a larger metabolic energy supply to perform the same amount of COM work as an individual with an efficient gait. While higher gait efficiency is likely to lead to greater gait economy, the subtle difference between the two terms is important. It is also important to note that the definition of gait efficiency defined here is not absolute and others have chosen to define gait efficiency in other ways. For example, gait efficiency has been previously defined as the total mechanical energy used during gait (as opposed to only the work performed on the COM) relative to the metabolic supply (van den Hecke et al., 2007).

Gait economy provides a "big picture" assessment relating the total energy it takes to move the entire body from point A to point B, only accounting for the distance the body moves between the points. Economy may be useful for assessing the functional impact of high energy demand, but it is not useful for identifying the underlying cause of the demand, and possible treatments. Gait efficiency, on the other hand, accounts for the mechanical work performed on the COM and provides a more precise picture of energy utilization. Gait economy is often assessed during clinical gait evaluations, and its value is typically presented as metabolic cost (metabolic energy expended per unit distance) (Waters & Mulroy, 1999). However, unlike gait economy, gait efficiency is not routinely calculated during clinical gait evaluations; although the data required for the calculation is regularly collected. An assessment of gait efficiency in CP may be beneficial insomuch that it may help explain the source of excessive metabolic demands.

In essence, gait efficiency is determined by the proportion of metabolic energy used to perform mechanical work on the COM relative to the total metabolic demand. For example, co-contraction, poor muscle timing, and excessive arm swing can all lower gait efficiency as they increase overall metabolic energy demands but do not increase the total mechanical energy of the body (Wakeling, Blake, & Chan, 2010).

To arrive at our measure of gait efficiency, we define 'useful energy' as the energy that is expended moving the body's COM relative to the environment. During gait, metabolic energy (*i.e.* energy supply), primarily derived from aerobic activity, is continuously converted to various forms of energy which may include internal work (work that does not directly lead to a displacement of the COM), external work (work performed on the COM relative to the surroundings), thermal work (body heat), and even sound (muscle by-product) (Barry, 1987; Schepens, Bastien, Heglund, & Willems, 2004; Willems, Cavagna, & Heglund, 1995). Using a more particular definition, the work performed on the COM relative to the environment is called COM work. Therefore, as walking is a continuous process, we define the useful energy rate as the time-rate at which COM work is being performed during walking (COM work rate). Additionally, we define the energy supply rate as the time-rate at which metabolic energy is being consumed during walking (MET rate). Using these definitions, gait efficiency can be defined as the COM work rate divided by the MET rate.

$$\text{Gait Efficiency} = \frac{\textit{Useful Energy Rate}}{\textit{Energy Supply Rate}} = \frac{\textit{COM Work Rate}}{\textit{MET Rate}} \tag{1}$$

In the clinical setting, the COM work rate can be computed using force plate data and step-to-step transition analysis techniques, while the MET rate can be measured through breath-by-breath gas analysis and indirect calorimetry (Cavagna, 1975; Donelan, Kram, & Kuo, 2002b; Waters & Mulroy, 1999).

Previous studies have used similar methods for estimating gait efficiency for both typically developed and hemiparetic adults (Detrembleur, Dierick, Stoquart, Chantraine, & Lejeune, 2003; Donelan, Kram, & Kuo, 2002a). In a study of TD adults, COM work was shown to be a major determinant of metabolic consumption; explaining 89% of the metabolic variance (Donelan et al., 2002a). Additionally, COM work was shown to be sensitive to changes in step length, step width, step frequency, and walking speed (Adamczyk & Kuo, 2009; Donelan, Kram, & Arthur, 2001; Donelan et al., 2002a, 2002b; Kuo, Donelan, & Ruina, 2005). Children with diplegic CP have been shown to produce more COM work and consume more metabolic energy than TD children during walking (Duffy et al., 1996; Kurz et al., 2010; Waters & Mulroy, 1999). However, the increase in work was not compared to changes in metabolic expenditure, and thus, the gait efficiency of children with diplegic CP has not previously been evaluated.

The purpose of this study was to investigate gait efficiency for children with diplegic CP in order to better understand the source of excessive metabolic demand typically observed for these individuals. We hypothesized that gait efficiency would be lower in children with CP as the relative increases in COM work reported in the literature do not appear to be large enough to account for the increases in metabolic demand observed for these individuals.

2. Methods

2.1. Study group

A representative sample of the pediatric ambulatory diplegic CP population seen at a regional treatment center was assembled by conducting a comprehensive search of our clinical database. Inclusion criteria were:

- diagnosis of diplegic CP