NOTE TO USERS

THE HIGH ENERGY COST OF WALKING IN CHILDREN AND ADOLESCENTS WITH SPASTIC CEREBRAL PALSY: PHYSIOLOGIC, ELECTROMYOGRAPHIC AND BIOMECHANICAL IMPLICATIONS

by

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A Thesis

Submitted to the School of Graduate Studies

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THE HIGH ENERGY COST OF WALKING IN CEREBRAL PALSY

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TITLE: The high energy cost of walking in children and adolescents with spastic cerebral palsy: physiologic, electromyographic and biomechanical implications

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ABSTRACT

Six studies (Studies 1-6) were performed to gain insight into selected physiologic (metabolic, cardiorespiratory, thermoregulatory), electromyographic, and biomechanical implications of the high energy cost of walking in children and adolescents with mild cerebral palsy (CP). Controls (CON) were also tested in Studies 3 and 4.

Studies 1 and 2 examined issues related to habituation to treadmill walking. The purpose of Study 1 was to determine if after one, 12-15-minute treadmill walking practice session: i) metabolic and cardiorespiratory responses during walking are affected by repeated walking bouts on different days, and ii) if these responses are different at different speeds. After 12-15 minutes of treadmill walking practice, subjects walked on the treadmill (3-minute bouts) at 60, 75, 90% of the fastest walking speed (FWS), on three different days. From Day 1 to Day 3, net ventilation ($\dot{V}_E$) and net heart rate (HR) at 90% FWS decreased by 3.6 l·minute^{-1} and 8 beats·minute^{-1}, respectively. There were no differences between Day 1 and Day 2 or Day 1 and Day 3 for any other metabolic or cardiorespiratory variable at any speed. Between-day reliability of most metabolic and cardiorespiratory responses was ≥ 0.95. Since there were no Day 1 to Day 3 differences in metabolic variables, Day 1 to Day 3 decreases at 90% FWS in net HR may reflect reduced emotional stress over time and decreases in net $\dot{V}_E$, an uncoupling of oxygen uptake ($\dot{V}O_2$) and $\dot{V}_E$. Despite between-day differences, it appears that reliable metabolic and cardiorespiratory data may be obtained in these subjects after one, 12-15-minute treadmill walking practice session.

In Study 2 the subjects practiced walking on the treadmill as in Study 1 and, on a different day, they then walked once on the treadmill for three minutes, at 90% FWS. In this case, the purpose of the study was to determine: i) minute-by-minute differences in lower limb antagonist muscle co-activation and stride length during a 3-minute treadmill walk following 12-15 minutes of treadmill

walking practice, and ii) if the minute-by-minute pattern of co-activation is affected by site (thigh or lower leg) and lower limb dominance. During the treadmill walk, non-dominant thigh co-activation decreased between minute 1 and a) minute 2 (6%), b) minute 3 (7.2%). Co-activation for the dominant lower leg decreased between minute 1 and minute 3 (11.3%). Non-dominant thigh co-activation was on average 27.3% higher than for the dominant thigh, independent of time. Thigh co-activation was on average 27.7% higher than for the lower leg, independent of dominance or time. Stride length increased between minute 1 and minute 3 by 2.1%. These data suggest that 12-15 minutes of treadmill walking practice may be sufficient time to obtain stable co-activation and stable stride length by minute 2 of a fast treadmill walk. The data also suggest that dominance and site affect the magnitude of co-activation.

The purpose of Studies 3 and 4 was to determine if children and adolescents with mild spastic CP differ from CON in their thermoregulatory responses during exercise in the heat, where such exercise would have the same oxygen (O_2) cost for both groups (Study 3) and where such exercise would have a higher O_2 cost for those with CP compared to CON (Study 4). Each subject with CP was individually matched to a CON. The CP subject and their CON-match arm-cranked (Study 3) or walked on the treadmill (Study 4) at the same intensity for three, 10-minute bouts in 35 °C, 50% relative humidity. In Study 3, there were no CP-CON differences in $\dot{V}O_2$ or in thermal strain. In Study 4, $\dot{V}O_2$, body temperatures, and HR were higher in the CP group compared to CON ($\dot{V}O_2$ was 40% higher, rectal temperature was 0.4 °C higher). Those with CP demonstrated greater thermal strain than CON during treadmill walking where they required more metabolic energy, and thus produced more metabolic heat than CON, but not during arm-cranking where their $\dot{V}O_2$ was matched and heat production was therefore similar between the groups.

The primary purposes of Studies 5 and 6 were to determine whether there was a relationship between the subjects' level of habitual physical activity (PA)

and their O_2 cost of walking (Study 5) or their biomechanical walking economy (Study 6). In both studies subjects walked on the treadmill at the same speeds and with the same amount of practice as in Study 1. HR (Study 5) and movement (Study 6) were also monitored over 2 weekdays and 1 weekend day. In Study 5 habitual PA (derived from monitored HR) was related (r = -.70 to -.84) to net $\dot{V}O_2$ at 60 and 75% FWS, to net $\dot{V}O_2$ m^{-1}, averaged across the three speeds, and to % peak $\dot{V}O_2$ at all three speeds. PA was not related to net $\dot{V}O_2$ at 90% FWS. In Study 6, biomechanical walking economy, as measured by the biomechanical economy quotient (BEQ), at 60, 75 or 90% FWS explained about half of the inter-subject variance in PA as measured by accelerometer movement counts. A similar relationship was found between BEQ and accelerometer movement counts at or above the 80^{th} and 90^{th} percentile for both the total minutes d^{-1}, and the number of 5-minute bouts d^{-1}. The data from Studies 5 and 6 suggest that PA in these subjects may be related to their walking economy.

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"I am a part of all that I have met." – Alfred, Lord Tennyson

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LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	analysis of variance
BEQ	biomechanical economy quotient
BSA	body surface area
CM	co-activation measure
COM	centre of mass
CON	control(s)
CP	cerebral palsy
CV	coefficient of variation
CWS	comfortable walking speed
EE	energy expenditure
EMG	electromyographic, electromyography
FWS	fastest walking speed
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
HR	heart rate
HR_{ex}	exercise heart rate
HR_{rec}	recovery heart rate
O_2	oxygen
P	probability
ρ	rho
PA	physical activity
PAL	physical activity level
R	intra-class correlation coefficient
r	Pearson correlation coefficient
RER	respiratory exchange ratio
RH	relative humidity
RPE	Rating of Perceived Exertion
RR	respiratory rate
SL	stride length
T_{re}	rectal temperature
ΔT_{re}	change in rectal temperature
T_{sk}	skin temperature
ΔT_{sk}	change in skin temperature
$\dot{V}CO_2$	carbon dioxide output
$\dot{V}_E$	ventilation
$\dot{V}O_2$	oxygen uptake
$\dot{V}O_{2PEAK}$	peak oxygen uptake
$\%\dot{V}O_{2PEAK}$	percent of peak oxygen uptake

FORMAT AND ORGANIZATION OF THE THESIS

This thesis was prepared in the "sandwich thesis" format as outlined in the McMaster University School of Graduate Studies March 2003 publication, "Guidelines for the Preparation of Thesis" and the additional requirements as described in the Medical Sciences Program 2003-2004 "Guide to Graduate Studies". The thesis consists of six original papers that are either published (Chapters 3 and 5), in press (Chapter 6), or under review for publication (Chapters 4, 7 and 8). Each of these chapters is formatted according to the requirements of the journal in which it was or is to be published. These chapters are preceded by an introduction that sets the context for the complete body of research (Chapter 1) and a chapter detailing the methods or referring the reader to the chapter (paper) in which the detailed methods are described (Chapter 2). The thesis concludes with a summary and discussion of the main findings and the future research directions that stem from these findings (Chapter 9). Selected questionnaires and data sets from the research described in the thesis are presented in the Appendix. The reader should be aware that since Chapters 3-8 are each complete descriptions of an experiment, including an introduction to set the context of the experiment and a discussion of the results, some of the material in Chapter 1 and Chapter 9 is also covered in these other chapters.

CONTRIBUTIONS TO A MULTI-AUTHORED BOOK CHAPTER AND PAPERS

CHAPTER 1, Sections 1.2.1-1.2.6

PUBLICATION

Unnithan, V. B., and D. B. Maltais. Pediatric Cerebral Palsy. In: Clinical Exercise Physiology: Application and Physiological Principles. L. M. LeMura and S.P. von Duvillard (eds.). Philadelphia: Lippincott Williams and Wilkins, pp. 285-299, 2004.

Contributions

D. B. Maltais wrote the sections of the book chapter which are featured in this thesis as Sections 1.2.1-1.2.6. V.B. Unnithan wrote other sections of the book chapter. These are not part of the thesis.

CHAPTER 3

PUBLICATION

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Contributions

The experiment was designed by D. B. Maltais, who was assisted by the co-authors. D. B. Maltais collected the data with the technical assistance of N. Huybrechts, B. Smith, and B. Timmons. Data reduction and processing were performed by D. B. Maltais. The data were analyzed by D. B. Maltais following consultation with M. L. Schmuck. D.B. Maltais wrote the paper with assistance from the co-authors. The primary supervisor for this study was O. Bar-Or.

CHAPTER 4

PUBLICATION

Maltais, D. B., M. R. Pierrynowski, V. Galea, H. de Bruin, N. Al-Mutawaly, and O. Bar-Or. Minute-by-minute differences in co-activation during treadmill walking in cerebral palsy. *Electromyography and Clinical Neuorophysiology* (In Review).

Contributions

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CHAPTER 5

PUBLICATION

Maltais, D. B., V. B. Unnithan, B. Wilk, and O. Bar-Or. Responses of children with cerebral palsy to arm-crank exercise in the heat. *Medicine and Science in Sports and Exercise.* 36(2):191-197, 2004.

Contributions

The experiment was designed by D. B. Maltais, who was assisted by the co-authors. D. B. Maltais collected the data with the technical assistance of B. Wilk. Data reduction and processing were performed by D. B. Maltais. The data were analyzed by D. B. Maltais following consultation with C. Goldsmith. D. B. Maltais wrote the paper with assistance from the co-authors. The primary supervisor for this study was O. Bar-Or.

CHAPTER 6

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CHAPTER 7

PUBLICATION

Maltais, D. B., M. R. Pierrynowski, V. Galea, and O. Bar-Or. Physical activity level is associated with the O_2 cost of walking in cerebral palsy. *Medicine and Science in Sports and Exercise* (In Review).

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CHAPTER 1: INTRODUCTION

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1.1 Thesis Rationale and Overview

Children and adolescents with cerebral palsy (CP), compared to their able-bodied peers, have a higher oxygen (O_2) cost of walking (Campbell and Ball, 1978; Duffy et al., 1996; Johnston et al., 2004; Rose et al., 1990; Rose et al., 1993; Unnithan et al., 1996a), which is associated with high antagonist muscle co-activation in the lower limbs (Unnithan et al., 1996a) and high total body mechanical power (Unnithan et al., 1999). The O_2 cost of locomotion in this population can be reduced by interventions designed to improve walking proficiency, such as ankle foot orthoses (Maltais et al., 2001) and orthopedic surgery (Dahlbäck and Norlin, 1985; Schwartz et al., 2004). Little is known, however, about the implications for these children and adolescents of their high energy cost of locomotion.

Six studies (Chapters 3-8) were undertaken to answer questions about selected implications. Three studies (Chapters 3, 4, and 8) investigated methodological implications related to habituation to treadmill walking, since it has traditionally been assumed that subjects should be habituated to walking on the treadmill prior to testing, to ensure the data from a treadmill walking protocol do not simply reflect an adaptation to the test. A treadmill walking protocol was used in this thesis because it allows for ease of data collection and control of walking speed. Several previous studies with this population have also employed a treadmill walking protocol, whether it was to compare the O_2 cost of walking in those with CP to that of their able-bodied peers (Rose et al., 1990; Rose et al.,

1993; Unnithan et al., 1996a), to assess peak oxygen uptake ($\dot{V}O_{2PEAK}$) (Hoofwijk et al., 1995), to determine mechanisms related to the high O_2 cost of walking in CP (Unnithan et al., 1999; Unnithan et al., 1996a), or to determine the effects of interventions (Dahlbäck and Norlin, 1985; Maltais et al., 2001; Massin and Allington, 1999). Habituation questions related to metabolic and cardiorespiratory variables were addressed in Chapter 3. In Chapters 4 and 8, habituation questions were addressed from the perspective of lower limb antagonist muscle co-activation (Chapter 4) and biomechanical walking economy (Chapter 8).

Four studies investigated more applied, as opposed to methodological, implications of the high energy cost of walking in CP. Two studies (Chapters 5 and 6) answered questions related to the implications of the O_2 cost, and hence metabolic heat production, of exercise to these subjects' thermoregulatory responses during exercise in the heat. Since Bar-Or (1983) has suggested that the increased energy cost of ambulation in CP may be one reason for their early fatigability (Dahlbäck and Norlin, 1985), the implications to these subjects' level of habitual physical activity (PA), of their high O_2 cost of walking, were studied in Chapter 7. Along the same lines, questions about the implications of their low biomechanical walking economy to their level of habitual PA, were addressed in Chapter 8. In Chapter 7, habitual PA was measured by monitoring heart rate (HR) and in Chapter 8, it was measured using accelerometry.

This thesis begins with an overview of the condition of CP (Section 1.2). The literature pertaining to the high O_2 cost of walking in CP is then discussed (Section 1.3). Next, is a review of measures that have been used to quantify co-activation during walking in this population (Section 1.4) and a review of biomechanical walking economy as relevant to CP (Section 1.5). Thermoregulation in children during exercise in the heat (Section 1.6.2), measurement of habitual PA in children (Section 1.6.3), and the level of habitual PA in those with CP (Section 1.6.4) are then discussed. Chapter 1 concludes with the overall purpose and hypothesis for this thesis (Section 1.7) and a list of

the specific purposes and hypotheses from each study (Section 1.8). The detailed methods used in the studies (Chapters 3-8), when not described already in detail in the relevant chapter(s), are found in Chapter 2. The thesis concludes (Chapter 9) with a general discussion of the research findings from Chapters 3-8 and suggestions for future research directions. Selected questionnaires from the studies and selected experimental data sets are presented in the Appendix.

1.2 What is Cerebral Palsy?

1.2.1 Description

Cerebral palsy is "an umbrella term covering a group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising early in development" (Mutch et al., 1992). In industrialized countries, CP occurs 2-2.5 times per 1000 live births.

1.2.2 Classification

Classification of CP is based on clinical descriptions of the type, topographic distribution, and severity (based on functional ability) of the motor impairment (Stanley et al., 2000a).

The type of motor impairment refers to certain attributes of muscle function. About 80% of children with CP are predominantly spastic, making it the most common type of CP. Spastic CP is characterized by muscles that demonstrate excessive stiffness, especially during movement. Spasticity in CP usually results from lesions or abnormalities of the motor cortex or the projections to and from the sensorimotor cortex. Those with dyskinetic CP are also often spastic, but chiefly demonstrate involuntary, writhing movements (athetosis), rigidity (dystonia), or both (Stanley et al., 2000a). With dyskinesia, there is involvement of the basal ganglia. Individuals with ataxic CP demonstrate poor co-ordination, instability, and jerky movements. Ataxia is due to lesions of the cerebellum or related structures.

Classification by topography refers to where on the body the motor impairment is seen. Those with quadriplegic CP usually demonstrate any one or more of the above types of motor impairments (spasticity, dyskinesia, ataxia) in the arms and legs, with about equal involvement of both (Minear, 1956). In quadriplegic CP, lesions are bilateral, but not necessarily symmetrical. Individuals with diplegic CP demonstrate spasticity in all four limbs, but much more so in the lower compared to the upper limbs (Minear, 1956). In diplegia there are also bilateral brain lesions, but they are typically more focal than in quadriplegia. With hemiplegic CP, there is spasticity on one side of the body only (Minear, 1956). Brain damage in hemiplegia is unilateral and, because of the path the motor tracts follow, the abnormality in the brain is contralateral to the hemiplegic side. Together, those with hemiplegic and diplegic CP account for 50-60% of children with CP in industrialized countries (Stanley et al., 2000a).

Classification by severity of the motor impairment refers (broadly) to the functional motor abilities of the child. According to Gage (1991), children are classified as having mild CP when they have very good functional movement with little limitation. They have moderate CP when they have some functional movement, but with definite limitations. Those with severe CP have minimal functional movement and are dependent on others or on technology for care and mobility. The Gross Motor Function Classification System (GMFCS) is another means of classifying by severity and is based on the child's functional mobility skills (Palisano et al., 1997). In general, GMFCS Levels I and II correspond to mild CP, Level III, moderate CP, and Levels IV and V, severe CP. For children 6 years of age and older, the mobility skill considered is walking. Those with Level I and II are able to walk without assistive devices (support). Children with Level III and IV require assistive devices to walk. Those with Level III may have difficulty walking outdoors. Some of them may use a manual or power wheelchair or scooter outdoors or in the community. Those with Level IV generally only walk for exercise. They are either pushed in a manual wheelchair or stroller or they use a

powered wheelchair or scooter for mobility. Children with Level V generally do not walk at all, are often restricted even in the use of a powered wheelchair or scooter, and thus rely on others for mobility. They are usually pushed in a manual wheelchair or stroller.

1.2.3 The Gross Motor Function Measure

The Gross Motor Function Measure (GMFM) is a valid and reliable tool to assess (as opposed to classify) abilities and change in children with movement abnormalities such as CP (Russell et al., 1989). GMFM scores, especially the Walking, Running, and Jumping dimension scores, have been shown to correlate with other physical performance measures used in CP, such as walking speed (Damiano and Abel, 1996; Drouin et al., 1996; Oeffinger et al., 2004), peak and mean lower limb anaerobic power (Parker et al., 1993), gains in knee flexor and extensor muscle strength (MacPhail and Kramer, 1995), and the O_2 cost of walking (Oeffinger et al., 2004). The Standing dimension scored and the Walking, Running, and Jumping dimension scores of ambulatory children and adolescents with CP (GMFCS Levels I-III) have also been shown to correlate (ρ = -0.72 and -0.77, respectively) with their GMFCS level (Oeffinger et al., 2004).

1.2.4 Associated Impairments

While impairment of the motor system is the main distinguishing feature of CP, brain lesions or abnormalities are seldom restricted to a single functional pathway. The most common associated impairments are sensory deficits such as blindness or deafness, learning disability, mental retardation, behavioural disorders, and seizure disorders (Stanley et al., 2000a). Children who have more severe CP are more likely to have other impairments, and the severity of these other impairments increases as the severity of the motor problem increases. Stanley et al. (2000a), for example, analyzed data from the population-based CP register of Western Australia and found only 4.4% of children with mild CP to

have marked cognitive impairment (IQ <35), as compared to over half (52%) of those with severe CP.

1.2.5 Risk Factors and General Prognosis

The motor impairments in CP result from damage to the structures concerned with movement: the motor cortex, basal ganglia, cerebellum, and the connections to and from these structures. Congenital anomalies, prematurity, low birth weight, and multiple pregnancy (> 1 fetus) are among the main risk factors for CP as they are associated with an increased rate of CP, but it is remains unknown if they cause CP (MacLennan, 1999). Although it is popularly believed CP is usually due to birth asphyxia, this is causal in only 8-10% of the CP population in developed countries (Blair and Stanley, 1988; Yudkin et al., 1995). In a recent review, Stanley et al. (2000b) concluded that CP rates are reduced by interventions that address the various risk factors. Among the interventions they considered highly efficacious were: i) delivery of premature infants in a specialized care facility, ii) limiting embryos implanted in fertility therapies to 3, and iii) treatment for infections in newborns.

In developed countries, about 90% of children with CP survive to adulthood (Evans et al., 1990; Hutton et al., 1994; Strauss et al., 1998). Life expectancy is reduced for those with severe mobility, feeding, and cognitive deficits (Evans et al., 1990; Strauss et al., 1998). With respect to prognosis for walking, children with CP who sit independently by 24 months are most likely to walk by about 8 years of age, at least for short distances indoors and with assistive devices (Paz Junior et al., 1994; Watt et al., 1989).

1.2.6 Overview of Pathophysiology

Since the majority of motor impairment research in CP pertains to the spastic type, the following discussion of pathophysiology is restricted to this type of CP. Spastic muscle is stiff. The muscle "resists" passive stretch at a shorter length than non-spastic muscle (Tardieu et al., 1982). This may occur because of

changes in the mechanical properties of muscle fibres (Berger et al., 1982), or because the muscle is shorter than normal. A decreased number of sarcomeres have been reported in animal models of spastic CP (Ziv et al., 1984). Movement also appears "stiff " because of increased co-activation of antagonist muscles (Crenna et al., 1992; Unnithan et al., 1996a). Increased co-activation in spastic CP is likely related to a lack of inhibitory supraspinal input to the motoneuron pool in the spinal cord as a result of the brain damage (Burke, 1988; Leonard et al., 1990).

Spastic muscle is also weaker than healthy muscle (Wiley and Damiano, 1998). The weakness may be related to some or all of the following: i) decreased excitatory supraspinal input due to the brain damage which results in fewer motor units being activated (Elder et al., 2003), ii) increased co-activation where the muscle is "weaker" because a portion of its force is expended overcoming the antagonist) (Elder et al., 2003; Wiley and Damiano, 1998), and iii) an increase in the ratio of low force-producing Type I fibres to high force-producing Type II fibres (Castle et al., 1979; Romanini et al., 1989; Rose et al., 1994).

Challenges (perturbations) to balance in those with CP result in excessive postural sway, indicating that balance is compromised in this population (Nashner et al., 1983). Suggested causes of balance deficits are: i) the spastic muscles that "effect" the balance strategies are weak, ii) the sequencing of muscle activation for balance strategies is abnormal, and iii) the anticipatory balance strategies that minimize the amount of displacement during a balance challenge are greatly decreased (Nashner et al., 1983).

The end results of stiff and weak muscles, increased antagonist muscle co-activation, and poor balance are seen in most motor activities of those with spastic CP, including walking. Although there is much variability in their gait patterns due to the variability within the condition and of the interventions children undergo, there are some common gait patterns (Perry, 1992b). Table

1.1 summaries one typical gait pattern, "crouch gait", which can be present in ambulatory individuals with CP, independent of their level of severity.

1.2.7 Subjects Studied in this Thesis

The detailed descriptions of the subjects with CP who were studied in this thesis are in the Methods and Results sections, respectively, of Chapters 3-8. These subjects had the more common spastic diplegic and hemiplegic types (and topographic distributions) of CP. When a treadmill walking exercise protocol was used, the subjects were able to walk without support (severity of CP: GMFCS Levels I and II). Testing in these instances was limited to subjects with Levels I and II because it was not possible to control for the amount of support a subject might take through the upper limbs if holding on to the treadmill handrails. The O_2 cost of treadmill walking is known to vary with the extent of support taken through the handrails (Green and Foster, 1991). Aside from the ability to walk without support, no attempt was made to control for the specific type of gait pattern a subject might employ. All subjects studied had sufficient cognitive and sensory abilities to follow instructions.

1.3 The High Oxygen Cost of Walking in Cerebral Palsy

1.3.1 Overview

The O_2 cost of walking over ground at a comfortable walking speed (CWS) is higher in those with CP as compared with able-bodied controls (CON) when that cost is considered over a distance such as a metre (Table 1.2). The difference in the O_2 cost between those with CP and their able-bodied peers can vary greatly. Campbell and Ball (1978) reported an over 3-fold higher O_2 cost of walking in a group of children and adolescents with spastic diplegic CP as compared with their peers. Duffy et al., (1996) on the other hand, found their subjects with spastic hemiplegic CP to have an O_2 cost 75% higher than CON. Johnston et al. (2004) reported that their subjects with mild CP (GMFCS Level I)

Table 1. 1. Example of a crouch gait pattern in spastic cerebral palsy

- Spasticity and shortening of the hip and knee flexor and ankle plantar flexor muscles result in increased flexion of the hips and knees and increased plantar flexion of the ankles during gait
- Spasticity and shortening of the ankle plantar flexors limit the smooth progression of the body forward over the feet; there is increased excursion in the vertical plane and the gait appears to have a "bouncing" quality
- Spasticity and shortening of the hamstring muscles restrict forward placement of the advancing leg, both by limiting the amount of forward hip flexion and by limiting knee extension; the child takes small steps with the anterior portion of the foot often making the initial contact
- Spasticity and shortening of the hip flexors limit hip extension in the stance leg as the swing-leg progresses forward to make initial contact with the ground, which contributes to both the increased excursion in the vertical place and to the short steps
- Movement in all planes is increased because balance strategies, which minimize excessive movement, are compromised

Adapted from: Perry (1992b)

Table 1. 2. The oxygen cost of walking over ground at a self-selected comfortable walking speed in children and adolescents with cerebral palsy compared to able-bodied controls.

Reference	Subjects	Walking Speed* $m\ s^{-1}$	Oxygen Uptake*
(Campbell and Ball, 1978)	CP = 22; 5-15 yr; SDi = all 9 walked with support	0.71 (0.004)	22.9 (6.17) ml kg^{-1} min^{-1} 0.86 (0.85) ml kg^{-1} m^{-1}
	CON = 6-13 yr (Historical CON group)	1.22 (0.02)	18.1 (3.30) ml kg^{-1} min^{-1} 0.25 (0.05) ml kg^{-1} m^{-1}
(Duffy et al., 1996)	CP, SDi = 13, 4-12 yr	0.79	28.0 ml kg^{-1} min^{-1} 0.64 ml kg^{-1} m^{-1}
	CP, SH = 6, 5-7 yr Need for support while walking not reported	0.82	20.3 ml kg^{-1} min^{-1} 0.42 ml kg^{-1} m^{-1}
	CON = 16, 5-12 yr	1.03	18.0 ml kg^{-1} min^{-1} 0.24 ml kg^{-1} m^{-1}
(Johnston et al., 2004)	CP = 30; 6-13 yr Level I = 5 Level II = 10 Level III = 9 Level IV = 6	CWS (actual speeds not reported)	0.28 ml kg^{-1} m^{-1} 0.44 ml kg^{-1} m^{-1} 0.63 ml kg^{-1} m^{-1} 2.17 ml kg^{-1} m^{-1}
	CON = 27, 7-13 yr		0.23 ml kg^{-1} m^{-1}

CP = cerebral palsy; SDi = spastic diplegia; CON = control group; SH = spastic hemiplegia; CWS= comfortable walking speed; Level = Level of severity as per the Gross Motor Function Classification System, only Levels I and II walk without support
*Group mean (SD, where reported)

had O_2 cost values 20% higher, whereas their subjects with severe CP (GMFCS Level IV) had values 8-fold higher than CON. These data suggest that the O_2 cost of over ground walking in those with CP may be related to the severity of the CP (or the extent of the motor involvement). This appears to be the case according to recent work by Oeffinger et al. (2004). These researchers measured O_2 consumption ($\dot{V}O_2$) per metre during over ground walking at self-selected CWS in 419, 4-21 year old subjects with CP (Level I-III). They found a positive, linear relationship (ρ = .61) between the O_2 cost of walking and the level of severity of CP. In addition, there was a negative linear relationship between the O_2 cost of walking and GMFM scores on the Standing dimension (ρ = -.70) and the Walking, Running, and Jumping dimension (-.68). Those with a lower O_2 cost of walking had higher scores on the GMFM dimensions related to walking.

Data from studies assessing the O_2 cost of treadmill walking in CP compared to CON are summarized in Table 1.3. When the CP and CON subjects walk at the same absolute speed, $\dot{V}O_2$ is higher in the CP group. As with over ground walking, the data for treadmill walking suggest that the O_2 cost of walking may be related to the severity of the motor involvement. Unnithan et al. (1998) found that subjects with spastic diplegic CP had a higher O_2 cost of treadmill walking than those with spastic hemiplegic CP and a lower cost than those with quadriplegic CP.

Bar-Or (Bar-Or, 1983) has suggested that the high O_2 cost of walking for children and adolescents with CP might be one cause of their early fatigability (Dahlbäck and Norlin, 1985). The literature suggests that two sources of this high O_2 cost of walking are high lower limb antagonist muscle co-activation (Unnithan et al., 1996a) and high total body mechanical power (Unnithan et al., 1999), (see Sections 1.4 and 1.5 for further discussion).

Table 1.3. The oxygen cost of treadmill walking in children and adolescents with cerebral palsy compared to able-bodied controls.

Reference	Subjects	Treadmill Belt Speed* $m\ s^{-1}$	Oxygen Uptake*
(Rose et al., 1990)	CP = 13; 7-16 yr SDi = 4; SH = 9 Some# walked with support	0.93 (0.33) FWS	23.4 (7.0) ml kg^{-1} min^{-1} 0.417 ml kg^{-1} m^{-1}**
	CON = 18; 7-17 yr	2.03 (0.23) FWS	25.1 (5.0) ml kg^{-1} min^{-1} 0.206 ml kg^{-1} m^{-1}**
(Rose et al., 1993)	CP = 12; 8-16 yr SDi = 9; SH = 3 Some# walked with support	0.36 0.63	14.25 (3.67) ml kg^{-1} min^{-1} 19.08 (7.20) ml kg^{-1} min^{-1}
	CON = 18; 7-17 yr	0.36 0.63	8.63 (1.27) ml kg^{-1} min^{-1} 10.55 (1.24) ml kg^{-1} min^{-1}
(Unnithan et al., 1996a)	CP = 9; 12.7 (2.8) yr* SDi = 7; SH = 1, SQ = 1 All walked without support	0.83	16.6 (6.5) ml kg^{-1} min^{-1}
	CON = 9; 13.6 (2.1)yr*	0.83	10.2 (1.2) ml kg^{-1} min^{-1}

CP = cerebral palsy; SDi = spastic diplegia; SH = spastic hemiplegia;
FWS = fastest walking speed; CON = control group; SQ = spastic quadriplegia
*Group mean (SD, where applicable)
** not reported, calculated based on mean walking speed reported for group
#Actual number who required support to walk not reported

Hinged ankle foot orthoses (Maltais et al., 2001), orthopedic surgery (Dahlbäck and Norlin, 1985; Schwartz et al., 2004), medication (botulinium toxin injections) to reduce spasticity (Massin and Allington, 1999), and use of a posterior vs. an anterior walker (Park et al., 2001) have all been shown to reduce the O_2 cost of walking in those with CP. Most interventions resulted in about a 10% decrease in the group mean O_2 cost of walking. One of the studies, that assessed the effects of orthopedic surgery, reported a 5% decrease in $\dot{V}O_2$ during walking (Dahlbäck and Norlin, 1985). The effect on the O_2 cost of walking of wearing hinged ankle foot orthoses varied from no effect at CWS to a 10% decrease while walking at 90% FWS (Maltais et al., 2001). Subjects who underwent a dorsal root rhizotomy showed a trend ($P = 0.37$) for a 10% decrease in the group mean O_2 cost of walking (Schwartz et al., 2004). The authors suggested that with 10 subjects, they did not have sufficient power to detect statistically significant differences (Schwartz et al., 2004).

Although, compared to their able-bodied peers, the O_2 cost of walking is higher in those with CP; their $\dot{V}O_{2PEAK}$ using a treadmill walking protocol is lower. Hoofwijk et al. (1995) tested nine, 10-16 year old subjects, most of whom had spastic diplegia and all of whom could walk without support on the treadmill. Their group mean $\dot{V}O_{2PEAK}$ was 32.7 ml kg^{-1} $minute^{-1}$ which was 28% lower than the CON group mean. The reasons for this low $\dot{V}O_{2PEAK}$ have not been systematically studied. One potential cause could be an early fatigue (Dahlbäck and Norlin, 1985) related to their high $\dot{V}O_2$ during walking (Bar-Or, 1983).

Several studies have assessed the effect of exercise training on $\dot{V}O_{2PEAK}$ or maximal mechanical power, by using either cycle or arm ergometry protocols, (Bar-Or et al., 1976; Berg, 1970; Ekblom and Lundberg, 1968; Lundberg et al., 1967; van den Berg-Emons RJ et al., 1998). The reported increases were between 8 and 32%. Only one study, however, employed a randomized clinical trial design (van den Berg-Emons RJ et al., 1998). In this study maximal aerobic

power increased by 32% following 9 months of 4 times weekly, 45-minute sessions of aerobic exercise.

1.3.2 Methodological Considerations I: Accounting for Body Size

When the magnitude of a physiologic variable such as $\dot{V}O_2$ is related to body size, accounting for size-related, inter-subject differences in the variable may or may not be relevant depending on the design of the study, and thus the research question(s). When the design is a within-subject (repeated measures) type as in Chapters 3, 5 and 6, for example, accounting for inter-subject, size-related differences in $\dot{V}O_2$ and associated variables is not especially relevant. Interpretations of regression analyses as in Chapter 7, however, are made under the assumption that inter-subject differences in the O_2 cost of walking do not simply reflect inter-subject size differences, but rather walking impairment differences. Whether walking impairment is related to body size in CP is an interesting question, but beyond the scope of this thesis. When the analyses warrant it, the effect of body size on the O_2 cost of walking in pediatric locomotion studies is usually accounted for by using a ratio standard; that is, considering the O_2 cost per unit of body mass (kg) (Morgan, 2000). This method was used in Chapter 7. The rationale for using this ratio standard for the $\dot{V}O_2$ data collected during walking or running is that body mass can be easily and accurately measured and it is the body mass that the individual lifts during walking or running (Rowland, 1996).

Tanner (1949) demonstrated that unless the physiologic variable changes proportionally with body mass, use of the body mass ratio standard could distort the values. If, for example, the variable increases at a proportionally slower rate than does body mass, the values for lighter children will be inflated in comparison to those of heavier children (Tanner, 1949). In pediatric exercise science there is no universally accepted method for accounting for body size-related differences in $\dot{V}O_2$ (Rowland, 1998; Welsman and Armstrong, 2000). Dimensional theory

suggests that $\dot{V}O_2$, as a volume per unit of time, is proportional to body length^2, which is proportional to body mass$^{2/3}$. Others (McMahon, 1973) have suggested that the theoretic body mass scaling exponent for $\dot{V}O_2$ is 3/4. This scaling exponent is based on an engineering analysis of the elastic properties of animals that ensure structural integrity of the load bearing structures during gait (McMahon, 1973).

In O_2 cost of locomotion studies with healthy children and adolescents, the empirical findings, which are based on allometric modeling methods to determine scaling exponents for body mass, have shown exponents of, or very close to, both 2/3 (Rogers et al., 1995) and 3/4 (Sjodin and Svedenhag, 1992). A scaling exponent of 0.90, however, has also been found (Armstrong et al., 1999). These studies with sample sizes of 12 (Rogers et al., 1995), 42 (Sjodin and Svedenhag, 1992), and 194 (Armstrong et al., 1999), may be too small to show stable scaling factors (Batterham and Jackson, 2003) and thus the scaling factors reported in these studies may not be representative of the population. Moreover, since none of these studies reported a 95% confidence interval for the scaling factor, one can not determine from the data whether the scaling factors differ statistically from each other or indeed, whether they differ from one.

1.3.3 Methodological Considerations II: Accounting for Walking Speed

As with body size, speed of walking or running affects $\dot{V}O_2$. O_2 cost of locomotion studies often compare subjects walking at the same speed or speeds (Morgan, 2000), which avoids any need to account for inter-subject differences in walking speed. This was essentially the case for the experiments described in Chapters 3, 5 and 6, which, as discussed above, were within-subject designs. Accounting for differences in $\dot{V}O_2$ and related variables due to walking speed is relevant to the experiment described in Chapter 7, where individually determined relative speeds, 60, 75 and 90% of the subject's fastest treadmill walking speed,

were used. For this experiment, $\dot{V}O_2$ per kg body mass was considered both over time (minute) and over a distance (metre).

Mechanical work, which incurs a metabolic cost, is defined as the change in the energy level of a system. This change in energy level can be determined by summing the changes in translational kinetic energy, rotational kinetic energy and potential energy of all body segments. Translational kinetic energy, which has the largest impact on mechanical work during walking, varies with velocity^2 (Hamill and Knutzen, 1995). Thus it has been assumed that theoretically, given a sufficiently large range in walking velocities (from very slow to very fast) $\dot{V}O_2$ should vary with the square of walking velocity or speed. In healthy adults, Ralston (1958) found this theoretical exponential relationship between treadmill locomotion speed and $\dot{V}O_2$, with the O_2 cost, $\dot{V}O_2$, ml kg^{-1} minute^{-1} = 0.00110v^2 + 5.9 , where v = walking velocity, m minute^{-1}. Corcoran and Brengelmann (1970) found a similar $\dot{V}O_2$-speed relationship between O_2 cost and walking speed for healthy adults walking on the ground. For walking velocities under 100 m minute^{-1}, Waters et al. (1988) found a linear relationship, with $\dot{V}O_2$, ml kg^{-1} minute^{-1} = 0.129v + 2.60, where v = walking velocity, m minute^{-1}. They (Waters, 1992) showed that the values obtained using this equation were very close to those that would be obtained using the equations of Ralston or Corcoran and Brengelmann, as long as walking speeds are below about 100 m minute^{-1} (1.67 m s^{-1}). A linear $\dot{V}O_2$-speed relationship has also been shown for healthy children and adolescents walking on the ground (Waters et al., 1988) and for children with CP walking on the treadmill (Rose et al., 1989). The data of Rose et al. (1989) appear to show a linear relationship between walking speed and O_2 cost per kg body mass for children with CP when walking just below their maximum speed. The relationship for healthy children in the study of Rose et al. appears quadratic, although regression equations are not reported. Values and relationships depicted by Rose et al., however, should be considered with caution, given that gait pattern and $\dot{V}O_2$ may have been altered by children

holding on to the handrails, which they were allowed to do at will. In summary, there is a theoretic, quadratic relationship between the O_2 cost of walking and walking speed. Experimentally, it appears that for walking speeds other than those that are very fast, (or perhaps very slow) the relationship between $\dot{V}O_2$ and walking speed may be essentially linear.

1.3.4 Methodological Considerations III: Habituation to Treadmill Walking

Treadmill walking protocols are frequently used in O_2 cost of locomotion studies in children and adolescents (Morgan, 2000). Use of a treadmill allows speed to be more precisely controlled than during over ground walking and physiologic, electromyographic (EMG) and biomechanical variables to be easily collected over several consecutive minutes. Control of walking speed may be especially relevant in intervention studies. The effect of hinged ankle foot orthoses on the O_2 cost of walking, for example, is speed dependent (Maltais et al., 2001).

To ensure the data from a treadmill walking protocol do not simply reflect an adaptation to the test, it has traditionally been assumed that subjects should be habituated to walking on the treadmill prior to testing. The literature for habituation to treadmill walking with respect to $\dot{V}O_2$ and related variables, for healthy children and those with CP, is reviewed in the introductory paragraphs in Chapter 3. In summary, the limited information available suggests that, as a group, healthy 7-11 year old children whose gait pattern has matured, require very little time to habituate to walking on the treadmill, perhaps as little as 20 s (Frost et al., 1995). Younger, healthy 6 year old children may require more treadmill walking practice (> 5 minutes) before there are no significant differences in $\dot{V}O_2$ between the walks (Tseh et al., 2000). Children with mild hemiplegic CP showed no between-trial (within-day) differences in the O_2 cost of walking following 5 minutes of treadmill walking practice (Keefer et al., 2002). It is unknown whether, after one practice session, $\dot{V}O_2$ would remain stable or if it

would further be reduced due to habituation, if subjects were tested on different days. It is also unknown whether any effects on $\dot{V}O_2$ of repeated walking bouts would be different at different speeds. The study in Chapter 3 was designed to address these unknowns for a group of children and adolescents with mild CP. Such information may be useful for researchers using a treadmill walking protocol to assess the effect of an intervention on walking economy.

1.4 Lower Limb Antagonist Muscle Co-activation

1.4.1 Review of Relevant Measures

Antagonist muscle co-activation, as the term implies, refers to concurrent activation of antagonistic muscles (Berger et al., 1984). In this thesis, unless stated otherwise, the term "co-activation" alone refers to that which occurs between antagonist muscles or muscle groups. Executing a motor task using an increased amount of co-activation implies increased metabolic energy expenditure (EE), as more muscle must be supplied with energy to perform the task. Hence those who walk using a greater amount of co-activation could incur a greater relative metabolic cost. From a mechanical perspective, co-activation, especially during gait, is a means of increasing joint stiffness and reducing agonist force production (Falconer and Winter, 1985). In those with CP, high co-activation has been attributed to central nervous system damage (Berger et al., 1984; Bowsher et al., 1992; Brunt and Scarborough, 1988; Crenna et al., 1992; Unnithan et al., 1996b; Unnithan et al., 1996a) as well as to a need for increased postural stability (Berger et al., 1984; Brunt and Scarborough, 1988; Crenna et al., 1992). As with scaling for body mass or walking speed, there is no agreement in the literature on the optimum method for quantifying the magnitude of lower limb antagonist muscle co-activation during walking in children and adolescents with CP.

The most thoroughly investigated method for quantifying the magnitude of lower limb antagonist muscle co-activation during walking in children and

adolescents with CP is that which was originally developed during the doctoral work of Frost (1995). The method was developed to explain, in part, the age-related changes in the O_2 cost of treadmill locomotion in healthy children and adolescents. In these studies that were later published (Frost et al., 1997; Frost et al., 2002), Frost defined the magnitude of co-activation as the area of overlap of the ensemble-averaged linear envelopes derived from the EMG data from two antagonist muscles or muscle groups, divided by the number of data points. In her studies the two antagonist muscle groups at the thigh were vastus lateralis and hamstrings. At the lower leg they were tibialis anterior and soleus. The EMG amplitude of each muscle (group) was normalized to the larger of that from either a maximal voluntary isometric contraction or the peak amplitude during a 3-s data collection.

Unnithan et al. (1996b; 1996a) used the same method and measure of co-activation (collecting data over 5 s) to examine patterns of co-activation during treadmill walking in children and adolescents with mild (mostly spastic diplegic) CP and healthy CON. Co-activation at the thigh and lower leg explained about 43 and 51% of the variance, respectively, in the inter-subject O_2 cost of walking at 0.83 m s^{-1} (Unnithan et al., 1996a). Co-activation at both the thigh and lower leg was also higher in those with CP compared to able-bodied CON at both 0.83 m s^{-1} and 90% FWS (1996b; Unnithan et al., 1996a). The CP group also had a higher O_2 cost of walking at 0.83 m s^{-1} compared to CON. Co-activation at both sites, for both groups was higher at the faster speed of 90% FWS compared with 0.83 m s^{-1}. At both speeds, for both groups, co-activation was higher at the lower leg compared to the thigh. In summary, the data of Unnithan et al. suggest that differences in lower limb antagonist muscle co-activation may explain at least some of the inter-subject differences in the O_2 cost of walking among subjects with CP. The high O_2 cost of walking in those with CP (compared to CON) may also be due, at least in part, to their higher level of co-activation. The subjects' increased co-activation with increased walking speed, and higher co-

activation in the lower leg compared to the thigh, may reflect a greater requirement for stiffness, either when walking at faster compared to slower speeds, or at the ankle compared to the knee during walking in general.

Bowsher et al. (1992) developed a co-activation measure to determine the magnitude of co-activation at the hip and knee (hamstring and quadriceps muscle groups) during the swing phase of gait in children and adolescents with spastic diplegic CP and healthy CON. The subjects walked over ground at self-selected CWS and FWS. Ensemble-averaged linear envelopes with the EMG amplitude normalized to each muscle group's peak value were used to quantify co-activation. The magnitude of co-activation was determined by contrasting the level of EMG activity of the two antagonist muscles groups and relating this to torque generated at the hip or knee at each instant in time. For this measure, 0 indicated minimal, and 1 indicated maximal co-activation. Unlike the findings of Unnithan et al. (1996b; 1996a), co-activation at the hip and knee increased with speed only for the CON (Bowsher et al., 1992). Speed did not affect co-activation in the subjects with CP (Bowsher et al., 1992). It is unknown whether the different findings in the two studies are due to the different methods for calculating co-activation, the different walking surfaces (treadmill and over ground) or the differences in absolute speeds at the slow and fast speed conditions. Although no absolute walking speeds were reported in the study of Bowsher et al., it is possible that inter-speed differences were not sufficiently large in the subjects with CP to elicit speed-related differences in co-activation, since these two speeds were self-selected. Their way of determining co-activation may also suffer from methodological limitations. It appears possible, for example, to have a co-activation value greater than zero with no EMG activity in one of the antagonist muscle groups, when using this method.

More recently Damiano et al. (2000) reported patterns of antagonist muscle co-activation at the thigh (rectus femoris and biceps femoris) during over ground walking in mostly spastic diplegic CP using a measure that is a

modification of the one used by Unnithan et al. (1996b; 1996a). In this method, however, after the EMG amplitude data were scaled to their isometric maximum, the data were weighted by a percentage of normal strength, based on previously published CON data. This weighting was an attempt to correct for possibly inflated EMG amplitudes, after scaling to a maximum voluntary isometric contraction, in muscles that have low absolute EMG output (Damiano et al., 2000). Co-activation was considered over the gait stride. Similar to the findings of Unnithan et al. (1996b; 1996a), but in contrast to those of Bowsher et al. (1992), co-activation increased with walking speed and was higher at the freely selected FWS compared to the freely selected CWS. Damiano et al. also estimated the energy cost of walking, using net HR per metre walked. In contrast to the findings of Unnithan et al. (1996a), Damiano et al. found a strong negative, linear relation between their HR cost of walking measure and thigh co-activation at both the CWS ($r = -.71$) and FWS ($r = -.90$). Inter-study comparisons regarding the relationship between the energy cost of walking and co-activation should be made with caution. The HR data in this more recent study were available for only six of the ten subjects and it is unknown whether these data were representative of the group. Moreover, the strength of correlations with such small sample sizes can be unstable (Norman and Streiner, 2000). Unlike the $\dot{V}O_2$ data in the study of Unnithan et al. (1996a), HR in this more recent study were not measured simultaneously with EMG, but was collected during the 5^{th} minute of a 5-minute walk. The EMG data were collected during a different (12 metre) walk. HR itself is also a less precise measure of metabolic EE than $\dot{V}O_2$ (Keefer et al., 2004a). Wearing hinged ankle-foot orthoses for example, resulted in an up to 10% decrease in the O_2 cost of walking, but no change in HR (Maltais et al., 2001). Thus methodological issues related to small sample size, differences in the time EMG and $\dot{V}O_2$ data were measured, and use of a less precise (than $\dot{V}O_2$) measure of the metabolic cost of walking may have combined to obscure any relationships between the energy cost of walking and co-activation in this study.

Although it is intuitively attractive to correct EMG amplitude data for force-related differences between antagonist muscles, the method of Damiano et al. (2000) may have limited application with the CP population. It might only be feasible for measuring co-activation at the thigh, since voluntary isometric contractions of the ankle plantar and dorsiflexors may not be feasible in subjects with even mild CP (Unnithan et al., 1996b; Unnithan et al., 1996a). Moreover, this newer method requires extra equipment and time to test isometric muscle strength, which could increase subject burden. The method also requires appropriate CON subject isometric strength data.

The most recently reported co-activation measure was used to quantify thigh (vastus lateralis and medial hamstrings) co-activation during treadmill walking (5 minutes at 0.67, 0.89 and 1.12 m s^{-1}) in subjects with spastic hemiplegic CP (Keefer et al., 2004b). This method is a modification of that of Falconer and Winter (Falconer and Winter, 1985). Keefer et al. defined the magnitude of co-activation as the ratio of twice the area of overlap of the linear envelopes of the antagonist muscles to the sum of the total area of both linear envelopes, expressed as a percentage. Zero would be minimal, and 100% would be maximal co-activation. The EMG amplitude data from the ensemble average linear envelopes for each muscle were normalized to their mean linear envelope amplitude value. The EMG data were measured for 6 s at some point (unspecified) during each treadmill walk. Co-activation was considered over the gait stride. The effect of walking speed on co-activation was not assessed. Contrary to the findings of Unnithan et al. (1996a), there was no significant linear relationship at any speed, between the O_2 cost of walking and thigh co-activation, either that on the hemiplegic side, or the average value from both thighs (Keefer et al., 2004b). The measure used by Unnithan et al. may be more sensitive to inter-subject differences in the O_2 cost of walking than that of Keefer et al. It is also possible that a $\dot{V}O_2$-co-activation relationship could not be detected by Keefer et al. due to low inter-subject variability in the O_2 cost of walking, since all

their subjects had the same type, distribution, and severity of CP. No information on their inter-subject variability in $\dot{V}O_2$, however, was reported. These authors (Keefer et al., 2004b) also did not find a difference in thigh co-activation between the hemiplegic and non-hemiplegic sides. This finding suggests that either there are compensatory increases in co-activation on the non-hemiplegic side in these subjects with CP (and hence no difference between the two sides) or that this measure is not sensitive to such intra-subject co-activation differences. The failure to find any meaningful co-activation patterns in this study may be due to a flaw in the methodology. Although it is unknown if co-activation remained stable during a treadmill walk in the Keefer et al. study, should co-activation patterns not be stable within a walk, it is possible that inter-subject differences in the time during the walk when EMG data were measured (which was not specified) obscured relevant co-activation patterns. Minute-by-minute differences in lower limb antagonist muscle co-activation were studied in Chapter 4.

1.4.2 Methodological Considerations: Habituation to Treadmill Walking

As stated above, it is has traditionally been assumed that subjects should be habituated to walking on the treadmill prior to testing to ensure the data from a treadmill walking protocol do not simply reflect an adaptation to the test. The literature for changes over time in EMG patterns in healthy individuals during walking is reviewed in the introductory section in Chapter 4. From these limited data (Hwang et al., 1994) it appears that it might be advantageous to have subjects with CP practice treadmill walking for well over 15 minutes and to have each walk last at least 7 minutes. This is unlikely to be feasible due to the time demands of such protocols and the risk of fatigue.

A 12-15-minute habituation protocol was found to yield reliable net metabolic and cardiorespiratory variables and is feasible for those with mild CP (Chapter 3). It is unknown, however, whether such a protocol would allow subjects with CP to obtain stable lower limb antagonist muscle co-activation values within a treadmill walk. It is also unknown whether co-activation site (thigh

or lower leg) or lower limb dominance affects the pattern of habituation. The study in Chapter 4 was designed to answer these unknowns. Information on inter-limb differences in co-activation could be useful to researchers and clinicians interested in motor control of those with CP and in the effects of interventions designed to improve motor control. Minute-by-minute differences in stride length within a treadmill walk were also assessed and the relevant literature reviewed in the introduction to Chapter 4. The method used by Unnithan et al. (1996b; 1996a) with modifications (see Methods, Chapter 4) was also used in this study because, as noted above, it requires no extra measurements of the subjects, is feasible for measuring co-activation at both the thigh and lower leg, and is sensitive to factors (the O_2 cost of walking, co-activation site and walking speed) that are relevant in CP.

1.5 Biomechanical Walking Economy

1.5.1 Overview

Walking is a repeating "sequence of limb motions to move the body forward while simultaneously maintaining stance stability" (Perry, 1992a). Work is done to advance the swing limb forward and maintain stance stability by controlling the falling body mass. The energy cost is determined by the amount of muscular effort used to perform these actions (Perry, 1992c). Effort, and hence metabolic or O_2 cost requirements, are reduced when mechanical energy is conserved. Energy conservation can occur through energy transfers (see next paragraph, below). Energy conservation can also occur if the individual does less work, independent of energy transfers, to complete the task (for example, less vertical lift of the body when walking). This latter aspect of mechanical energy conservation is the rational behind the measure discussed in Section 1.5.4. Thus when comparing two individuals, the one who has greater conservation of mechanical energy for a given walking task would be the more economical walker from a (bio)mechanical perspective.

1.5.2 Total Body Mechanical Power: Segmental Method

One method to assess mechanical energy conservation during gait is to calculate total body mechanical energy per unit of time (power). Unnithan et al. (1999) calculated total body mechanical power during treadmill walking (0.83 m s^{-1}) in children and adolescents with CP and healthy CON. They used a kinematic analysis of individual body segments. The algorithm devised by Pierrynowski et al. (1980) was used. Mechanical power was calculated assuming no energy transfers between body segments; that is, as if the law of conservation of energy was not valid. Mechanical power was also calculated assuming energy transfers within adjacent body segments (conversion of mechanical energy from transitional kinetic energy to rotational kinetic energy and back, and conversion of mechanical energy from potential energy to kinetic energy and back) as well as energy transfers between adjacent body segments within the same limb (assuming all segments of the same limb are linked by one conjoint muscle). Mechanical power per kg body mass was higher in the CP group compared to CON, independent of whether or not energy transfers were allowed in the model (Unnithan et al., 1999). Net $\dot{V}O_2$ per kg was also higher in the subjects with CP. For the CP group, there was a positive linear relationship between the O_2 cost of walking and total body mechanical power (assuming energy transfers). About 87% of the variance in the O_2 cost of walking could be explained by the total body mechanical power values that assumed energy transfers (Unnithan et al., 1999). These data suggest one cause of the high O_2 cost of walking in those with CP may be their high mechanical power and thus low conservation of mechanical energy (more work done in the CP group compared to controls, independent of mechanical energy transfers).

Jeng et al. (1996) measured HR and mechanical power during six treadmill walks at a comfortable speed, but with varying stride rates in children with mild hemiplegic CP. As with Unnithan et al. (1999), mechanical power was measured according to the methods of Pierrynowski et al. (1980). Net HR per

metre walked was highest at the lowest and highest frequency conditions (± 25% of the preferred frequency), but there was no significant difference among the frequency conditions for mechanical power. Jeng et al. (1996) suggested their findings indicate that children with hemiplegic CP optimize to some extent on the "physiologic" cost of walking, but not on mechanical energy conservation. It is, however, also possible that the range of frequency conditions was insufficient to elicit intra-subject differences in mechanical power in children with mild CP.

1.5.3 Limitations of the Segmental Method

The segmental approach to mechanical power calculations (Pierrynowski et al., 1980; Williams and Cavanagh, 1983) is the approach that must be taken with a treadmill walking protocol when one can not directly measure the forces exerted by the ground on the feet (ground reaction forces) nor calculate joint powers and moments. This approach, however, is fraught with assumptions and unknowns that threaten its validity (Aleshinsky, 1986).

One unknown is the source of the forces operating on a particular body segment. Only the resulting displacement of the segment over time is directly measured (Zatsiorsky and Gregor, 2000). Thus only a resultant force can be calculated for each body segment. The actual produced power or mechanical energy expended that caused the displacement of that segment over time is not known. What is known is the net power or work done on the segment (Zatsiorsky and Gregor, 2000). The effect of negative forces, and hence negative work, is unaccounted for. Work and power are likely underestimated, but the extent of the underestimation may not be constant, rather it will likely vary with the segment and the particular time point in the gait cycle. Assuming a constant negative to positive "efficiency ratio" as done by Frost et al. (2002) may or may not minimize the error.

Since the sources of the forces operating on a particular body segment are unknown, assumptions must be made about the transfer of forces, that is, the extent and location of conjoint muscles (Zatsiorsky and Gregor, 2000). One

commonly used approach is to allow transfer of energy within and between segments of the same extremity (Williams and Cavanagh, 1983). This, however, assumes that each extremity has one con-joint muscle, which is incorrect (Zatsiorsky and Gregor, 2000), and can lead to over estimations of the total mechanical power of the body.

Elasticity, that is, stored energy in the elastic components of muscle and associated tissue, is unaccounted for with the segmental approach to mechanical power calculations (van Ingen Schenau, 1998). It is unknown to what extent the work (force) of a muscle is due to concentric contraction and what is due to energy that was conserved in the elastic components of the muscles. This is especially relevant for muscles like the triceps surae that undergo stretch-shortening cycles (van Ingen Schenau, 1998). The failure to account for stored elastic energy likely results in an over estimation of total mechanical power.

The segmental approach to mechanical power calculations does not account for co-contraction (Frost et al., 2002). Thus the calculated net work and power will be less than the produced work and power (underestimated total mechanical power). It has been suggested that the failure of the segmental model to account for co-contraction may be one of the reasons why mechanical power did not account for much of the variation in walking economy due to age in children (Frost et al., 2002), since co-contraction, as estimated by co-activation, was shown to decrease with increasing age (Frost et al., 1997).

It is has been suggested that use of the segmental method may cloud our understanding of the relationship between the metabolic EE and the body's power output, rather than clarify this relationship (van Ingen Schenau, 1998). It was noted above, for example, that differences in mechanical power account for only 4% of the variability in walking and running economy in children of different ages (Frost et al., 2002). While authors of this study rightly detail the limitations of their segmental approach to mechanical power calculation, it remains unknown whether mechanical power differences among children is or is not

associated with age-related changes in walking economy. Models that explain economy differences based on the assumption that mechanical power differences are not important, could therefore be misleading.

These weaknesses in the model used to assess total body mechanical power do not necessarily invalidate the conclusions of the findings of Unnithan et al. (1999). It is likely that the 5-fold difference (as estimated from graphed data) in the lowest to highest mechanical power values supercede any variability that would be due to weaknesses of the model. By contrast, in the study of Jeng et al. (1996) there is about a 2-fold difference (estimated from graphed data) in the lowest to highest mechanical power values. In this case, it perhaps remains unknown whether these children optimized on mechanical energy conservation. To assume they did not, as Jeng et al. did, could again be misleading.

1.5.4 The Biomechanical Economy Quotient

Mechanical energy conservation can be assessed more simply than by using a complex analysis of total body mechanical power. It is generally assumed that minimizing the vertical excursion of the body's centre of mass (COM) is one of the main means of conserving energy during gait (Perry, 1992c; Saunders et al., 1953). As described in the introductory section to Chapter 8, the biomechanical efficiency quotient (BEQ) (Kerrigan et al., 1996), which is the ratio of the measured vertical sacral excursion during a gait stride to that predicted from sacral height and stride length data, is a means of quantifying mechanical energy conservation and thus biomechanical walking economy. With the BEQ, a value of 1 is expected for individuals who are healthy with a mature gait pattern. It should be noted that athough the BEQ was originally named the biomechanical *efficiency* quotient, the term *economy* rather than efficiency is used in this thesis and thus in the thesis, the BEQ refers to the biomechanical economy quotient. The term economy is used rather than efficiency because efficiciency is not specially measured with the BEQ.

The equation for the predicted value of vertical sacral excursion during gait is based on a mathematical model the authors (Kerrigan et al., 1995) developed from the kinematic gait data of able-bodied adults. This equation is found in the introductory section to Chapter 8. Kerrigan et al. (1995) showed that independent of walking speed, sacral height, or stride length, the measured vertical displacement of the sacrum was about half of that predicted had the individual been walking with a compass gait. Compass gait assumes the lower limbs are rigid levers without feet or ankle or knee joints, "roughly" similar to walking on the heels with the knees maintained in full extension (Saunders et al., 1953). This theoretic model was used by Saunders et al. (1953) to illustrate the motion patterns by which the healthy individual reduces excursions, especially vertical, of the COM (modeled as the sacrum) by about 50%. These six motion patterns are termed the "determinants of gait" (Saunders et al., 1953). As originally conceived these are:

1. Horizontal pelvic rotation, which reduces the amount the COM is lowered during double limb support.
2. Contralateral (to the support limb) pelvic drop (pelvic obliquity), which reduces the amount the COM is raised during single limb support.
3. Knee flexion during the stance phase, which also reduces the amount the COM is raised during single limb support.
4. Presence of a foot attached to the distal end of the shank (lower leg), which reduces the slope of the COM vertical excursion.
5. Presence of an ankle joint which also reduces the slope of the COM vertical excursion.
6. Lateral pelvic displacement, which is reduced (and thus so is lateral displacement of the COM), when weight is transferred from one leg to the other. This is accomplished by the presence of valgum at the knees, which allows the base of support, that is, the distance between the feet, to be

narrower than the distance between the hips and still allow the shanks to remain vertical.

Of these determinants, the first three were originally considered to be the principal mechanisms by which vertical sacral excursion is minimized (Saunders et al., 1953). It has recently been shown with healthy adults that these first three determinants of gait are second, third and fourth in importance in reducing the maximum vertical excursion of the modeled COM of the "compass gait" (Della et al., 2001). The main determinant of gait (means of reducing vertical sacral excursion) is heel rise from foot flat, which can be considered a refinement in the definition of the 4^{th} and 5^{th} gait determinants (Della et al., 2001). When vertical excursion of the modeled COM of actual gait is considered, heel rise accounts for about 2/3 of the total reduction in vertical sacral excursion (Della et al., 2001). Pelvic rotation, pelvic obliquity, and knee flexion during stance are of minor importance (Della et al., 2001; Gard and Childress, 1997; Gard and Childress, 1999). Heel rise raises the COM at its lowest point and thus reduces its over all vertical excursion (Kerrigan et al., 2000). It is unknown what determinants affect vertical excursion of the sacrum in those with CP.

The BEQ avoids assumptions inherent in the segmental model to calculate total body mechanical power. As discussed in the introductory section to Chapter 8, previous research has shown the BEQ to be sensitive to changes in walking proficiency in adults and children with various neurological impairments (Kerrigan et al., 1996). As well, pilot data from the lab where the BEQ data were collected for this thesis (Human Movement Lab, McMaster University) shows the BEQ to be reliable (between-day) in healthy adults as well as in children and adolescents with mild CP during treadmill walking. The BEQ was therefore used to measure biomechanical walking economy in the study in Chapter 8. This study investigated, in children and adolescents with mild CP, the relationship between habitual PA and biomechanical walking economy, and whether walking speed (treadmill belt speed) affected biomechanical economy.

1.6 The High Energy Cost of Walking in Cerebral Palsy: Practical Implications

1.6.1 Overview

Four studies (Chapters 5-8) were undertaken as a part of this thesis to answer questions about selected, practical implications, to children and adolescents with mild spastic CP, of their energy cost of exercise. Two studies (Chapters 5 and 6) addressed the implications of the O_2 cost of exercise to these subjects' thermoregulatory responses during exercise in the heat. The implications to their level of habitual activity, of their high O_2 cost of walking and low biomechanical walking economy, were addressed in Chapters 7 and 8, respectively.

1.6.2 Thermoregulatory Responses during Exercise in the Heat

Physical activity results in the production of metabolic heat. This heat has to be dissipated or an increase in body temperature will occur. Body core temperatures above 39 °C will interfere with cell functions and thus health. Since, compared to healthy children, those with CP have a higher O_2 cost of walking per kg body mass, they have to dissipate a greater metabolic heat load during such locomotion activities. Whether thermoregulatory responses of children and adolescents with CP differ from those of their able-bodied peers is unknown.

As reviewed by Malina et al. (2004), heat transference between the body and the environment in humans occurs by conduction, convection, radiation and evaporation. The skin-environment temperature gradient determines the rates of conduction, convection and radiation. When the skin temperature is higher than that of the environment, for example, heat flows from the skin to the environment. Since the body surface area to mass ratio is higher in children than in adults so too are the rates of conduction, convection and radiation. Under the human body's control are two mechanisms to dissipate heat: an increase in skin blood

flow, which increases the heat transference from the body core to its surface, and sweating, the mechanism by which evaporative cooling occurs with wet skin.

Children have lower sweating rates than adolescents who in turn have lower sweating rates than adults do (Bar-Or, 1980; Falk et al., 1992a). Since the number of sweat glands is inversely proportional to body surface area (Bar-Or, 1989), the increased sweating rate with age is due to an increase in sweat production per gland. Children, however, show greater increases in skin blood flow than adolescents or adults (Drinkwater et al., 1977; Falk et al., 1992b).

Although thermoregulation has not been studied in those with CP, when adults with hemispheric brain infarction are exposed to a heat stimulus at rest, the paretic side of the body, compared to the non-paretic side, shows increased sweating (Korpelainen et al., 1993) and decreased skin temperature (Korpelainen et al., 1995). It is not known whether these responses influence the ability of these individuals to dissipate excessive body heat during exercise in a warm climate. Should such responses exist in children or adolescents with CP, however, this could have a greater impact on them than on the adults due to the higher body surface area -to-body mass ratio in children and adolescents relative to adults and the greater likelihood that they (children and adolescents) will be physically active outdoors.

Use of a walking exercise protocol, however, would not allow the effect on thermoregulation of such mechanisms to be assessed independent of between-group (CP vs. able-bodied CON) metabolic heat production. Using an upper body exercise protocol such as arm cranking could provide a means of matching the metabolic heat production of those with mild CP to that of able-bodied CON. This would allow for investigation of the effect of CP on body temperature responses to exercise in the heat, independent of between-group differences in metabolic heat production. Such a study is described in Chapter 5, where thermoregulatory responses during arm cranking exercise in the heat were compared between children and adolescents with mild spastic CP and able-bodied CON. The CON

were matched individually to those with CP for body size and maturation, since as noted above, these affect thermoregulatory responses. The impact of the high O_2 cost of walking on thermoregulatory responses of those with CP was also assessed in Chapter 5. In this study a treadmill walking exercise protocol was used.

1.6.3 Habitual Physical Activity I: Measurement Techniques

Physical activity is "any bodily movement produced by skeletal muscles that results in caloric expenditure" (Caspersen et al., 1985). Free living PA can be measured subjectively, using direct observation or questionnaires (diaries, recall questionnaires or interviews) (Sirard and Pate, 2001). It can also be measured objectively using physiologic measures such as HR, the doubly-labeled water method or electronic motion sensors (Sirard and Pate, 2001).

Direct observation can be time-consuming, as it requires proper training of the observers and adequate control of inter- and intra- observer reliability. The method is useful when information on the type, frequency, duration, and context of the activity is desired, that is, PA behaviour information. Given the time consuming, but potentially accurate nature of this method, it is often used as a standard or criterion measure (Sirard and Pate, 2001). There are no published studies, to the best of this author's knowledge, that have used this method to quantify or describe PA in those with CP. Questionnaires, by contrast, are low cost and for the most part, easy to use. They also measure PA behaviour. Children, due to their immature cognitive ability, however, may not accurately recall intensity, frequency and duration of PA (Sallis, 1991). Questionnaires have been used to describe habitual PA in children and adolescents with CP (Longmuir and Bar-Or, 2000). Since the accuracy of this method has not been established for the CP population, at best questionnaires can be considered a measure of these individuals' perceptions of their PA.

The doubly-labeled water technique, in which the subject ingests a dose of a labeled isotope ($^2H_2{}^{18}O$), measures total EE by determining carbon dioxide

production from the differing elimination rates of the labeled hydrogen, which is only eliminated from the body as water, and the labeled O_2, which is eliminated as both water and CO_2 (Schoeller et al., 1986). When basal or resting EE is measured, the EE of PA can be determined. PA is often quantified as PA level (PAL), which is the ratio of total EE to resting or basal EE. The doubly labeled water technique, while accurate, is expensive and technically complicated (Sirard and Pate, 2001). For children with CP, the method has been used to quantify their PA (Bandini et al., 1991; van den Berg-Emons et al., 1995) and as a criterion measure to validate the more feasible FLEX HR method (van den Berg-Emons et al., 1996). The details on the FLEX HR method are described in Chapter 2.

Monitored HR can be used to estimate EE because of the linear relationship between $\dot{V}O_2$ and HR. The FLEX HR method (Livingstone et al., 1992; Spurr et al., 1988) was designed to minimize the effect that factors other than PA can have on this $\dot{V}O_2$-HR relationship. As the method is accurate and feasible for quantifying PA in children with CP (van den Berg-Emons et al., 1996), it was used to quantify PA for the study described in Chapter 7, in which the relationship between the O_2 cost of walking in children and adolescents with mild CP and their habitual PA was investigated.

Electronic motion sensors estimate PA by detecting body movement. Their relatively low cost and low reactivity, that is, little influence on the subject's behaviour, make them especially suitable for larger scale studies. The reliability and validity of these sensors can vary greatly among devices (Sirard and Pate, 2001). Electronic motion sensors (accelerometer) have been used to quantify PA in adolescents and young adults with physical disabilities (van den Berg-Emons et al., 2001), but not specifically CP.

The RT3 is a motion sensor that measures acceleration in 3 planes. It was used to quantify habitual PA for the study described in Chapter 8. In this study the relationship between biomechanical walking economy and habitual PA was

assessed. The Introductory and Methods sections in Chapter 8 describe the rationale for using the RT3.

1.6.4 Habitual Physical Activity II: Mild Cerebral Palsy

Van den Berg-Emons (1995) compared the PAL of a group of 10 children with CP, 9 of whom were ambulatory, with that of able-bodied CON. Those with CP demonstrated a 15% lower PAL than CON. Aerobic exercise training may increase PAL in those with CP. Subjects with CP who took part in an exercise intervention program that was mostly aerobic in nature (four times weekly over 9 months) showed a trend for their PAL to be higher after training compared to before training (P=.07) (van den Berg-Emons RJ et al., 1998). The mechanisms that are related to the decreased level of habitual PA in those with CP are unknown, as are the mechanisms by which training might increase PA.

As noted several times in this introduction, it has been suggested (Bar-Or, 1983) that the low walking economy of children and adolescents with CP might be one cause of their early fatigability (Dahlbäck and Norlin, 1985). Those with low walking economy would be walking at a higher relative exercise intensity or % $\dot{V}O_{2PEAK}$, compared to more economical individuals, and thus they would have less "metabolic reserve", and would therefore fatigue sooner. Although this hypothesis has yet to be explicitly tested in children and adolescents with CP, in healthy running-trained boys who were assessed over a 2-5 year period, $\dot{V}O_{2PEAK}$ per kg body mass did not change over time, whereas running economy and endurance performance both improved (Daniels et al., 1978). Should low walking economy be associated with reduced endurance, the low PAL in boys and girls with CP may be a compensatory mechanism to reduce or prevent fatigue. As stated in the previous section, the relationship between PAL and the O_2 cost of walking was investigated in Chapter 7.

One of the factors associated with the high O_2 cost of walking in children and adolescents with CP is low biomechanical walking economy (poor

mechanical energy conservation) as indicated by high total body mechanical power (Unnithan et al., 1999) The implications of low biomechanical walking economy with respect to the low level of habitual PA in these individuals is unknown. Such information would be useful for researchers interested in a greater understanding of the implications of interventions designed to improve walking proficiency. As noted in the previous section, the relationship between habitual PA and biomechanical walking economy was investigated in Chapter 8.

1.7 Thesis Studies: Overall Purpose and Hypothesis

1.7.1 Purpose

The overall purpose of these studies was to gain insight into selected physiologic (metabolic, cardiorespiratory, thermoregulatory), electromyographic, and biomechanical implications of the high energy cost of walking in children and adolescents with mild spastic CP.

1.7.2 Hypothesis

The overall hypothesis was that the high energy cost of walking in children and adolescents with mild spastic CP would have specific physiologic, electromyographic and biomechanical implications.

1.8. Thesis Studies: Specific Purposes and Hypotheses

1.8.1 Study 1 (Chapter 3)

The purpose of this study was to determine if after one, 12-15-minute treadmill walking practice session: i) metabolic and cardiorespiratory responses during treadmill walking in children and adolescents with mild spastic CP are affected by repeated walking bouts on different days, and ii) these responses are different at different speeds. It was hypothesized that following 12-15 minutes of treadmill walking practice, there would be no between-day differences in metabolic and cardiorespiratory responses during walking at a relatively slow

speed, but that at faster speeds, the responses would be lower on Day 2 and Day 3 compared to Day 1.

1.8.2 Study 2 (Chapter 4)

The primary purpose of this study was to determine, in children and adolescents with mild spastic CP: i) minute-by-minute differences in lower limb antagonist muscle co-activation and stride length during a 3-minute treadmill walk following 12-15 minutes of treadmill walking practice done on a different day, and ii) if the minute-by-minute pattern of co-activation is affected by site (thigh or lower leg) and by lower limb dominance. A secondary purpose of the study was to determine, if overall, there was a difference in co-activation between the dominant and non-dominant lower limbs. It was hypothesized that, following 12-15 minutes of treadmill walking practice, stable lower limb co-activation would be established by the second minute of a 3-minute treadmill walk. It was also hypothesized that, independent of time and site, co-activation would be greater for the non-dominant compared to the dominant lower limb and that independent of dominance or time, lower leg co-activation would be greater than for the thigh.

1.8.3 Study 3 (Chapter 5)

The purpose of this study was to determine if children and adolescents with mild spastic CP differed from CON in their thermoregulatory response during exercise in the heat, where such exercise would have the same O_2 cost for both groups. We hypothesized that during short duration arm-crank exercise of the same relative intensity in a warm, moderately humid climate, children and adolescents with CP compared to healthy CON individually matched for age, body size, biological maturity, gender, and race, would demonstrate: i) similar metabolic heat production, ii) lower increases in rectal temperature, iii), lower increases in mean skin temperature, iv) similar HR and v) greater sweating rate.

1.8.4 Study 4 (Chapter 6)

The purpose of this study was to determine if children and adolescents with mild spastic CP differ from CON in their thermoregulatory response during exercise in the heat, where such exercise would have a higher O_2 cost for those with CP compared to the CON. It was hypothesized that during short duration treadmill walking exercise at the same speed and slope in a warm, moderately humid climate, children and adolescents with mild, spastic CP, compared to healthy CON individually matched for age, body size, biological maturity, gender, and race, would demonstrate: i) higher metabolic rates, ii) greater increases in rectal temperature, iii) greater increases in mean skin temperature, iv) a higher exercise HR, v) similar sweating rates, and vi) a higher rating of perceived exertion.

1.8.5 Study 5 (Chapter 7)

The primary purpose of this study was to determine, in children and adolescents with mild CP, whether there was a relationship between their level of habitual PA and O_2 cost of walking. Since these subjects also have reduced $\dot{V}O_{2PEAK}$ compared to their typically developing peers (Hoofwijk et al., 1995), a secondary purpose of this study was to determine if their habitual PA was related to their $\dot{V}O_{2PEAK}$. It was hypothesized that low levels of habitual PA would be associated with a high O_2 cost of walking and low $\dot{V}O_{2PEAK}$.

1.8.6 Study 6 (Chapter 8)

The primary purpose of this study was to determine, in children and adolescents with mild spastic CP, the relationship between biomechanical walking economy, as measured by the BEQ, and the mechanical aspect of habitual PA, as measured by the RT3 triaxial accelerometer. Since children and adolescents with mild CP are able to walk at different speeds both over ground and on a treadmill (Maltais et al., 2003; Unnithan et al., 1996a), the effect of treadmill belt speed on the BEQ and minute-by-minute BEQ differences within a

walk was also examined. It was hypothesized that there would be a positive linear relationship between habitual PA and biomechanical walking economy. It was also hypothesized that the subjects' walking proficiency would be less at more demanding, faster speeds and thus biomechanical walking economy would be lower at faster, compared to slower speeds. Since a 12-15-minute treadmill walking practice session appears sufficient for habituation from a metabolic walking economy perspective (Maltais et al., 2003), it was hypothesized that there would be no minute-by-minute differences in the BEQ within a walk at any speed. It was assumed that the subjects in this study would be habituated to walking on a treadmill according to published procedures (Maltais et al., 2003).

1.9. References

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CHAPTER 2: DETAILED METHODS

2.1 Methods Described in Detail in the Chapters

As the detailed methods used for these studies are, for the most part, found in the Methods sections of each chapter, or the relevant chapter (paper) is cited, the following is a list of the methods and where the details can be found in the chapters.

- The standardized procedures for habituating the subjects to walking on the treadmill and determining FWS as done in Chapter 3, 4, 6, 7, and 8 are described in Chapter 3, on page 79.
- The measurement procedures for resting metabolic and HR variables as done Chapters 3, 7, and 8 are described in Chapter 3, on page 79.
- The procedures for the measurement of physiologic variables during treadmill walking as done in Chapters 3, 6, and 7 are described in Chapter 3, on pages 79-80.
- The foot switch application as done in Chapter 3 is described in that chapter on page 80.
- The procedures and criteria for achieving steady state during treadmill walking as done in Chapters 3 and 6 are described in Chapter 3 on pages 81-82.
- To calculate EE in kJ minute^{-1} during walking (Chapter 3) or arm-cranking (Chapter 5), the $\dot{V}O_2$ values were converted to kJ using Equation 1 from Chapter 3 on page 81.
- The procedures for collection of EMG data and subsequent calculation of the co-activation measure as used in Chapter 4 are described in that chapter on pages 113-116.
- The set-up and procedures for arm-crank exercise as done in Chapter 5 are described in that chapter on pages 142-145.

- The procedures for the measurement of physiologic variables (body temperatures, metabolic rate, and HR) during treadmill walking as done in Chapters 6 are described in that chapter on pages 165-167 and pages 168-171.
- The procedures for the determination of mean skin and rectal temperatures and the change in these temperatures as done in Chapters 5 and 6 are first described in Chapter 5 on pages 145-146.
- The procedures for determining sweating rate as done in Chapters 5 and 6 are first described in Chapter 5 on page 146. The equation to calculate respiratory water loss (Mitchell et al., 1972) is as follows:

  Respiratory Water loss, g $minute^{-1}$ = 0.019 $\dot{V}O_2$, l $minute^{-1}$ (44 - Pa) (1)

  Where Pa = water vapour pressure, mm Hg, at 35 °C, 50% relative humidity (20.8 mmHg)
- The measurement procedures for temperature, metabolic and HR variables as done in Chapter 6 are first described in Chapter 6 on pages 165-167 and 169-171.
- The procedures for kinematic data collection and for the subsequent calculation of the BEQ as done Chapter 8 are first described in that chapter on pages 227 and 230-231.
- The procedures for the collection and processing of accelerometry data as done in Chapter 8 are described in that chapter on pages 227-229 and 231-232.

2.2 Methods Not Described in Detail in the Chapters

2.2.1 Peak Oxygen Uptake

Peak $\dot{V}O_2$ was determined during a treadmill walking protocol according to previously published methods (Hoofwijk et al., 1995). The method is described in detail in the following two paragraphs.

The treadmill, HR monitor and metabolic cart were those used as described in Chapter 3. The equipment set up and measurement of metabolic and HR data were as for the treadmill walks at submaximal exercise intensities as described in Chapter 3. Subjects were habituated to walking on the treadmill and their FWS was determined according to the procedures described in Chapter 3. After this procedure, they rested in the sitting position until HR was within 10% of its pre-exercise value. They then walked for one minute, during which time their self-selected (subject indicated whether they wished to walk faster or slower and researcher changed the speed) CWS was determined. They rested again in the sitting position until HR was within 10% of its pre-exercise value.

The $\dot{V}O_{2PEAK}$ test lasted 8-12 minutes. Each stage lasted 2 minutes. $\dot{V}O_2$ and HR were measured as described in Chapter 3 for the sub-maximal treadmill walks. The speed at which subjects began the test was dependent upon their subjective CSW on the treadmill. Those whose CWS was 0.56-0.97 m s^{-1} walked at 0.67 m s^{-1}. Those whose CWS was 0.97-1.39 m s^{-1} walked at 0.83 m s^{-1}. Those whose CWS was > 1.39 m s^{-1} walked at 1.00 m s^{-1}. The speed at stage 2 for each subject was approximately the speed at the midpoint between their starting speed and their FWS. For stage 3 they walked at their FWS. After stage 3, the gradient was increased by 2-5% for each stage. The change in the gradient for each of these subsequent stages was consistent within a subject. After stage 3 the subjects also walked about 0.05-0.14 m s^{-1} slower than their FWS. The speed was also constant after stage 3. The test was terminated when the subjects, in spite of encouragement, could not continue to walk. This they indicated by putting their hands firmly on the hand rails. If a subject had begun to lose balance or otherwise indicate distress, the researcher would have terminated the test. This, however, was not necessary. Peak $\dot{V}O_2$ was defined at the average of the two highest consecutive 20-s values within the same stage. Maximum HR was defined as the highest 15-s value.

2.2.2 FLEX HR Method to Determine Physical Activity Level

The procedures for measuring $\dot{V}O_2$ and HR in the lab and in the field (2 weekdays and 1 weekend day) are described in detail in Chapter 7. The details on determining PAL using the FLEX HR (Spurr et al., 1988) method as adapted for those with CP (van den Berg-Emons et al., 1996) follow.

Physical activity was defined as PAL, the ratio of total EE d^{-1} to resting EE d^{-1}. Total EE d^{-1} was calculated, using the methods described below, from the minute-by-minute HR monitored during the waking hours of three days (2 weekdays, 1 weekend day) and from the resting EE. It was assumed that most of the unmonitored hours were sleeping hours or time of very low PA. The interviews with the subjects confirmed that non-monitored waking hours were indeed hours of very low PA. Each subject's resting EE and their own unique HR-$\dot{V}O_2$ relationship were determined in the lab. Resting $\dot{V}O_2$ in l $minute^{-1}$ was the average of the $\dot{V}O_2$ values in the lying, sitting, and standing positions. These $\dot{V}O_2$ values were determined by averaging the six most consecutively stable 20-s values from each of the 4-minute data collection periods, with the exception of one subject where three consecutive 20-s values were used. We chose not to use a ventilated hood for the lying position because we wanted all resting data to be measured under the same conditions. HR was determined for each of the resting positions by averaging HR over the same period as was done for $\dot{V}O_2$. Four calibration points were used for each subject's HR-$\dot{V}O_2$ relationship. These were the HR and $\dot{V}O_2$ while standing, and the average HR and $\dot{V}O_2$ (the last 40 s) from the first three sub-maximal stages of the maximal exercise test. Two exceptions were for the first stage of the exercise test for 2 subjects where the average $\dot{V}O_2$ of the complete 2-mintue stage was used since these two subjects stumbled towards the end of this stage and $\dot{V}O_2$ during this time were correspondingly increased.

Prior to determining total EE from the three days of monitored HR, these data were screened for artifacts. Artifacts were defined as HR < 35 beats minute^{-1} > peak HR (Ekelund et al., 1999) and any sudden change in HR of > 60 beats minute^{-1} that lasted for only 1 minute (Kriemler et al., 1999). Peak HR was that which was measured during the maximal treadmill exercise test (see Section 2.1.1). These artifacts varied from 0.5-2.1% of the HR data. They were removed and replaced with HR values determined by averaging those HR data that were previous and subsequent to the artifact(s). No more that 4 minutes (4 values) of consecutive artifact data occurred for any subject. Total EE was determined using a modification of methods suitable and valid for children with CP (van den Berg-Emons et al., 1996) and originally validated in healthy individuals by Spurr et al. (1988). In this method a "FLEX" HR is determined, above which there is a strong HR-$\dot{V}O_2$ correlation and below which this correlation is not strong. The FLEX HR was defined as the mean of the highest HR from the resting values (those during standing) and the lowest HR from the exercise values (those during the first sub-maximal stage of the maximal exercise test). This definition was used for all but one subject whose HR in standing was 127 beats minute^{-1}, yielding a FLEX HR of 118 beats minute^{-1}. Examination of the three days of monitored HR data along with the information about activities gained from the interviews showed that a FLEX HR of 118 beats minute^{-1} for this subject would likely over estimate time spent in activities of low EE. For this subject, the highest HR during rest was defined as the average HR during lying, sitting and standing, which resulted in a FLEX HR of 108 beats minute^{-1}. For the group, FLEX HR was 105 ± 7.7 beats minute^{-1}.

EE for the monitored periods when HR was > FLEX HR was determined from each subject's HR-$\dot{V}O_2$ calibration curve. EE during the monitored periods when HR was ≤ FLEX HR was calculated based on the mean resting $\dot{V}O_2$ defined above. EE during the unmonitored portions of the three monitored days was also based on this resting $\dot{V}O_2$. Resting EE d^{-1} was determined from the

average of the three resting values, since the lying value was not always the lowest one. Total EE d^{-1} for each subject was therefore determined. For three of the 33 monitored days, the first 8.5 h were monitored, for two of the 33 days, the first 9 h were monitored. Since the missing hours were always at the end of the day and the interviews showed that the subjects engaged in resting-low intensity physical activities during this time, EE based on resting $\dot{V}O_2$ was used for these hours of missing data. In addition, due to equipment malfunction, one subject had HR data for one weekday and one weekend day (full 11 h for each day). As the interviews showed similar physical activities were performed on both weekdays, this subject's total EE d^{-1} was based on the two monitored days.

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CHAPTER 3: REPEATED TREADMILL WALKS AFFECT PHYSIOLOGIC RESPONSES IN CHILDREN WITH CEREBRAL PALSY

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3.1 Abstract

Purpose: To determine if physiologic responses during treadmill walking in children with cerebral palsy (CP) are affected by repeated walking bouts on different days, and if effects are different at different speeds. **Methods**: Three girls and five boys (9.2-15.7 yr, 23.3-64.4 kg) with mild CP received 12-15 minutes of treadmill walking practice and had their fastest walking speed (FWS) determined during an introductory visit. During each of three subsequent visits (Day 1, Day 2, Day 3), subjects walked for 3 minutes at 60, 75 and 90% FWS. Resting physiologic measures were taken on Day 1. **Results**: From Day 1 to Day 3, net ventilation ($\dot{V}_E$) and net heart rate (HR) at 90% FWS decreased by 3.6 l·minute^{-1} and 8 beat·minute^{-1}, respectively. There were no differences between Day 1 and Day 2 or Day 1 and Day 3 for any other physiologic variable at any speed. Day 3 was less than Day 2 for net HR (60% FWS) and, independent of speed, net $\dot{V}O_2$ (per kg body mass and per stride) and net energy expenditure (kJ·minute^{-1}). Between-day reliability (R) of physiologic responses was ≥ 0.95, except respiratory rate (R = 0.75). Intra-subject, between-day variability for the $\dot{V}O_2$ measures was 7.6-12.9%. **Conclusion**: Since there were no Day 1 to Day 3 reductions in metabolic variables, Day 1 to Day 3 reductions at 90% FWS in net HR may reflect decreased emotional stress over time and

reductions in net $\dot{V}_E$, an uncoupling of $\dot{V}O_2$ and $\dot{V}_E$. Despite between-day differences, reliable net physiologic and stable net metabolic variables may be collected in subjects with mild CP following one treadmill walking practice session.

3.2 Introduction

Cerebral palsy (CP) is a "group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising early in development" (19). It occurs 2 to 2.5 times per 1000 live births (24). A decrease in walking proficiency and economy (5,30) is a main physical disability of spastic diplegic and hemiplegic CP, which are the most common subtypes (23). High, lower limb antagonist muscle co-activation (30) and mechanical power (29) are associated with this low economy. Interventions to improve walking proficiency also increase walking economy; for example, orthopedic surgery (6) and bracing (15). Studies investigating mechanisms (30,29) and interventions primarily (6,15) used a treadmill walking protocol, which allows speed to be more precisely controlled than during over ground walking and physiologic, electromyographic and biomechanical variables to be more easily collected simultaneously. Control of walking speed may be especially relevant in intervention studies. The effect of hinged ankle foot orthoses on the oxygen cost of walking, for example, is speed dependent (15).

To ensure the data from a treadmill walking protocol do not simply reflect an adaptation to the test, it has traditionally been assumed that subjects should be habituated to walking on the treadmill prior to testing. In healthy 7-11 yr old children, who presumably have a mature gait pattern (26), Frost et al. (8) found no significant between-trial or between-day differences in oxygen uptake ($\dot{V}O_2$), heart rate (HR) or kinematic variables at various walking and running speeds following 15-20 s of treadmill walking practice. This suggests that, as a group, children whose gait pattern has matured require very little time to habituate to

walking on the treadmill. In younger, healthy 6 yr old children, however, whose gait pattern is likely not mature (26), $\dot{V}O_2$ during treadmill walking (1.34 $m \cdot s^{-1}$) even after 5 minutes of practice was significantly higher for the first trial than for trials 2 and 3 (within-day), although the difference was small (0.2 $ml \cdot kg^{-1}$ $minute^{-1}$) (28). Those under 7 years, perhaps due to their immature motor abilities related to walking (26), appear to require more treadmill walking practice before there are no significant differences in $\dot{V}O_2$ between the walks.

In children and adolescents with CP, who also have an immature walking pattern (12), walking practice sessions of 15-20 minutes prior to testing have been reported in the literature (9,15,30,29), although other studies (6,21) have not stated if or how much walking practice preceded testing. Following 5 minutes of treadmill walking practice, Keefer et al. (11) found no significant between-trial (within-day) differences in $\dot{V}O_2$ (trials 1 and 2 = 6.6 $ml \cdot kg^{-1} \cdot minute^{-1}$, trial 3 = 6.2 $ml \cdot kg^{-1} \cdot minute^{-1}$, $P < 0.05$) for 6-15 yr olds with spastic hemiplegic CP walking on the treadmill at 0.67 $m \cdot s^{-1}$. It is unknown whether, after one practice session, $\dot{V}O_2$ would remain stable, or if it would further be reduced due to habituation, if subjects were tested on different days. It is also unknown whether any effects repeated walking bouts have on $\dot{V}O_2$ would be different at different speeds. Such information would be useful for researchers using a treadmill protocol to assess the effect on walking economy of various interventions. Since the increase in walking economy when wearing orthoses (compared to wearing only shoes) in children with mild CP is greater at faster compared to slower speeds (15), and since there was no within-day improvement in walking economy (after one practice session) for those with CP with repeated walking bouts at a slow speed (11), improvements in walking economy due to repeated waking bouts on different days in this population may be greater at faster speeds.

The purpose of this study was to determine if after one, 12-15-minute practice session: i) metabolic and cardiorespiratory responses during treadmill walking in children and adolescents with spastic CP are affected by repeated

walking bouts on different days, and ii) these responses are different at different speeds. We hypothesized that following 12-15 minutes of treadmill walking practice, there would be no between-day differences in physiologic responses during walking at a relatively slow speed, but that at faster speeds the responses would be lower on Day 2 and Day 3 compared to Day 1.

3.3 Methods

Five boys and three girls, 9.2-15.7 yrs, with mild spastic CP (as determined by the Gross Motor Function Classification System (20) participated in the study (Tables 3.1 and 3.2). No subject had previous experience walking on a treadmill without handrail use. Six of the subjects regularly used treadmills 1-2 times per week while holding on to the handrails, which reflects the current practice in our area, in that treadmills are frequently used for rehabilitation. No one had undergone orthopedic surgery or taken medication to reduce spasticity within the preceding year. No subject wore braces and all walked without assistive devices. The degree of soft tissue contracture was similar in all subjects. They all had at least 105° of hip flexion and lacked no more than 20° of hip extension. Passive range of motion at the knee was full (tested with the hip extended) but subjects on average had about a 35° contracture (lack of knee extension with the hip at 90°) of the hamstring muscle group (bilaterally). Ankle dorsiflexion (knee extended) was at least neutral (0°). Subjects were otherwise healthy, involved in 2-3 h per week of recreational physical activity, outside of school hours (i.e., soccer, cycling, basketball, swimming), and on no medication that would affect the variables measured in the study. They refrained from caffeine for 3 h, eating for 2 h, and heavy exercise for 8 h before coming to the lab for each visit. Written, informed consent was obtained from subjects at or over the age of 14 yr. For subjects under 14 yr, written, informed consent was obtained from parents preceded by assent from the child. The study was approved by the McMaster University Research Ethics Board. Subjects were recruited through a local children's rehabilitation center.

Design. The participants visited the Children's Exercise and Nutrition Centre on 4 occasions. During the first, introductory visit, they were oriented to the laboratory and all equipment to be used in the study. Their fastest treadmill walking speed (FWS) was determined, as described below. Subjects returned for three subsequent visits. During each visit, they walked on the treadmill three times, for 3 minutes each time, at 60, 75 and 90% of their previously determined FWS. The order of speeds was randomized. There was a maximum of 2 weeks between the introductory and the first of the three treadmill walking visits. These subsequent three visits took place within 10.3 ± 5.5 days.

Measurements. *Visit 1 (Introductory Visit):* The subjects completed questionnaires about physical activity (modified from Bar-Or (1)), health status and diet (time, content and amount of the last meal and snack), with the assistance of a parent if needed. Pubertal stage (pubic hair for boys, breast development for girls) was self-determined, based on photographs (16) according to the criteria of Tanner (27). Total body length was estimated from arm span (Stanley metal tape measure, Canadian Tire Corp., Hamilton, ON, Canada) because not all subjects could stand erect. Body adiposity was estimated by summing the medians of three skinfold measurements taken at the biceps, triceps, subscapular and suprailliac sites on the dominant side. Body mass (Mott Electronic Scale, UMC1000, accuracy ± 10 g; Ancaster Scale Co. Ltd., Brantford, ON Canada) was measured after subjects emptied their bladder. To subsequently calculate nude body weight, clothes, including shoes, were also weighed (Accuba Scale, 1,200, accuracy ± 0.1 g). All children wore gym shorts, a T-shirt, socks and running shoes. The same shoes were worn for all visits. Topographic distribution of spasticity was based on the classification of Minear (18). One person (DM) determined the severity of gross motor involvement using the Gross Motor Function Classification System (20), a five-level grading system, where Level I refers to those with the mildest involvement. The degree of lower limb spasticity was assessed using the modified Ashworth Scale (2), a five level

scale (0 = no spasticity; 4 = rigidity) which is feasible and commonly used in this population (3,25). Lower limb passive range of motion (to screen for contractures) was assessed by goniometry using standardized techniques modified from McDowell et al. (17). Gross motor function was measured using the Walking, Running, and Jumping component of the Gross Motor Function Measure (22). This specific component relates to walking proficiency in children with CP (7). Walking proficiency was also determined by measuring the comfortable and fast walking speed on level ground (30 m walkway) using the median of a triplicate measurement. The order of ground walking speeds was randomized. Subjects rested in the sitting position between each trial until HR (Polar Vantage XL, Polar CIC, Port Washington, New York) was within 10% of its pre-exercise value.

Following the descriptive measurements, they were taught how to walk on a recently calibrated treadmill (Woodway Desmo M Tread Erogometer, Woodway USA, Waukesha, Wisconsin) without holding on to the handrails. Their FWS on the treadmill, defined as the fastest speed maintained for 3 minutes without loss of double limb support, was determined through a 3-stage protocol, with each stage lasting 3 minutes. The starting speed for this procedure was the subject's subjectively determined comfortable treadmill walking speed. They rested in the sitting position between walks until HR was within 10% of its pre-exercise value. In total, the subjects walked for about 12-15 minutes on the treadmill.

Visit 2-4 (Treadmill Walking Visits, Day 1, 2 and 3): Pre-exercise metabolic rate was measured in the sitting position for 5 minutes (after subjects rested for 15 minutes) to allow for subsequent calculation of the net metabolic cost of walking. This was done during Visit 2 only, to minimize the time burden on the subjects. Metabolic and respiratory data were measured with the child connected to an open circuit system by a mouth piece (Vmax29 SensorMedics Corp., Yorba Linda, CA, USA). HR was also monitored continuously by the Polar HR monitor and stored in the receiver as 5-s averages. Metabolic variables, $\dot{V}O_2$ and carbon

dioxide output ($\dot{V}CO_2$), and respiratory variables, minute ventilation ($\dot{V}_E$) and respiratory rate (RR), were recorded at 20-s intervals. The respiratory exchange ratio (RER), used for determination of energy expenditure, was calculated automatically from the $\dot{V}CO_2$ and $\dot{V}O_2$ data and also stored at 20-s intervals. Just prior to each data collection, gas flow was calibrated with a 3 l syringe. The O_2 and CO_2 analyzers were also calibrated at that time using gases of known concentration (O_2 = 16.00, 20.94, 26.00 %; CO_2 = 4.00, 0.05%; Balance N_2). After measurement of pre-exercise values, subjects walked on the treadmill for 3 minutes at 60, 75 and 90% of their previously determined treadmill FWS (0.67 ± 0.35 $m \cdot s^{-1}$; 0.83 ± 0.44 $m \cdot s^{-1}$; 1.01 ±0.54 $m \cdot s^{-1}$, respectively) while connected to the metabolic cart and wearing the HR monitor. Ventilatory expired gas and HR data were collected as during the pre-exercise measures. Subjects rested in the sitting position between walks until HR was within 10% of its pre-exercise value or remained steady and was no longer decreasing. To subsequently calculate the energy cost of walking per stride, the children wore custom-made foot switches. For each foot, switches were positioned and taped in place on the sole of the shoe at the heel and 1st, 3rd and 5th metatarsal heads. The four leads from each foot converged into a single lead, which was plugged into a small junction box attached to an elastic belt worn by the subject. A single lead from the junction box connected the subject to an A/D conversion system (CODAS, Dataq Instruments Inc., Ohio), that sampled the signal at 1000 Hz. Foot switch data was used to determine stride rate (see next paragraph, below).

Calculations and Data Reduction. To determine if steady state was reached, the mean $\dot{V}O_2$ from the 2nd and 3rd minute of each treadmill walk were compared. Steady state was defined as a difference in $\dot{V}O_2$ of < 2 $ml \cdot kg^{-1}$ $minute^{-1}$ between minutes 2 and 3. $\dot{V}_E$ ($l \cdot minute^{-1}$), RR ($breath \cdot minute^{-1}$), RER and HR ($beat \cdot minute^{-1}$) for each trial were determined by averaging these data over this same 1-minute period of steady state (3rd minute of each walk) as chosen for $\dot{V}O_2$. Sitting metabolic, respiratory and HR values were calculated by

averaging the three consecutively lowest 20-s values from that 5-minute sitting collection period. The net values for $\dot{V}O_2$, $\dot{V}_E$, RR, RER, HR for each treadmill walk were calculated by subtracting the sitting values from the walking values. $\dot{V}O_2$ per kg body mass ($\dot{V}O_2$–kg) for each walk was calculated by dividing net $\dot{V}O_2$ by the total body mass of the subject, including clothes and equipment. The O_2 cost per stride ($\dot{V}O_2$-stride, ml·stride^{-1}) of each trial was calculated by dividing net $\dot{V}O_2$ during walking by the mean stride rate of the of walk (strides·minute^{-1}). Stride rate was determined from the heel switch data using custom software (written by one of the authors, MRP). To calculate net energy expenditure (EE, kJ·minute^{-1}) during walking, the sitting, and steady state $\dot{V}O_2$ from each walk were first converted to kJ using the following equation:

$\dot{V}O_2$, l (during analysis period) x (3.815 + 1.232 x RER)*x 4.186** (1)

* Regression equation created from the data of Lusk (14)

** Conversion factor for determining energy in kJ from kcal

Net EE was determined by subtracting sitting EE from walking EE.

Statistical Analyses. Between-day and between-speed differences in metabolic and cardiorespiratory variables and the effect of the treadmill belt speed on the pattern of between-day differences was determined using a 2-way, repeated measures ANOVA. Tukey's HSD *post-hoc* test was used to identify pairs that were significantly different. Alpha was set at .05. Between-day reliability of these same variables across all speeds was measured by calculating the intraclass correlation coefficient (R). Intra-subject (between-day) variability was determined by calculating the coefficient of variation (CV, %), at each speed, for each variable. Statistical analyses were done with Statistica software, Version 5.5 (StatSoft Inc, Tulsa, OK).

3.4 Results

Steady State. When mean $\dot{V}O_2$ from minute 2 and minute 3 of each walk were compared to determine if a steady state was achieved, there were no differences ≥ 2 $ml \cdot kg^{-1} \cdot minute^{-1}$ (8) in the group data. For individual subjects, steady state was achieved in 81% of the treadmill walks.

Metabolic variables. Independent of treadmill belt speed, net $\dot{V}O_2$-kg was lower on Day 3 than on Day 2 (P = 0.049). There was no significant difference between Day 2 and Day 1, or between Day 3 and Day 1 at any speed (Table 3.3). Net $\dot{V}O_2$-kg was higher when subjects walked at 90 than when they walked at either 60 (P = 0.0006) or 75% FWS (P = 0.008). There was no significant difference between 60 and 75% FWS (Table 3.3). Between-day reliability of net $\dot{V}O_2$-kg was high (R, Table 3.4). Intra-subject, between-day variability was lowest when subjects walked at 90% FWS and highest when they walked at 75% FWS (CV, Table 3.4). Net $\dot{V}O_2$-stride showed the same pattern as net $\dot{V}O_2$-kg. Irrespective of speed, Day 3 values were lower than on Day 2 (P = 0.02), but not significantly different than on Day 1, nor were they different on Day 2 compared to Day 1 (Table 3.3). Net $\dot{V}O_2$-stride was higher when subjects walked at 90 than when they walked either 60 (P = 0.02) or 75% FWS (P = 0.04). There was no significant difference between 60 and 75% FWS (Table 3.3). Between-day reliability of net $\dot{V}O_2$ was high (R, Table 3.4). Intra-subject, between-day variability was lowest when subjects walked at 90% FWS and highest when they walked at 75% FWS (CV, Table 3.4). Net EE (independent of speed) was also lower on Day 3 compared to Day 2 (P = 0.04), with no significant difference between Day 2 and Day 1, nor between Day 3 and Day 1 (Table 3.3). When subjects walked at 90% FWS, net EE was higher than when they walked at 60% FWS (P = 0.01). Net EE at 75% FWS was not significantly different than at 60 or 90% FWS (Table 3.3). Between-day reliability of Net EE was high (R, Table 3.4). Intra-subject, between-day variability was lowest when

subjects walked at 90% FWS and highest when they walked at 75% FWS. (CV, Table 3.4).

Respiratory variables. Net $\dot{V}_E$ was lower on Day 3 than on Day 1 (P=0.04) and Day 2 (P = 0.03), but only when subjects walked at 90% FWS (Fig. 3.1). When subjects walked at 90 % FWS, net $\dot{V}_E$ was higher than when they walked at 60% FWS (P = 0.01). There were no differences in net $\dot{V}_E$ at 75% compared to 60 or 90% FWS (Fig. 3.1). Between-day reliability of net $\dot{V}_E$ was high (R, Table 3.4). Intra-subject, between-day variability was lowest when subjects walked at 90% FWS and highest when they walked at 60% FWS. (CV, Table 3.4). Repeated treadmill walks on different days did not affect net RR at any speed (Table 3.3). When subjects walked at 90% FWS, net RR was higher than when they walked at 60 (P = 0.0005) and 75% FWS (P = 0.02). There was no significant difference when subjects walked at 75 and 60% FWS (Table 3.3). Between-day reliability of net RR was moderate (R, Table 3.4). Intra-subject, between-day variability was overall high, but lowest when subjects walked at 60% FWS and highest when they walked at 75% FWS. (CV, Table 3.4).

Heart rate. When subjects walked at 90% FWS, net HR was lower on Day 3 than on Day 1 (P = 0.0004, Fig. 3.2), but Day 2 values were not significantly different from those on Day 1 or Day 3 (Fig. 3.2). When they walked at 60% FWS, net HR was lower on Day 3 than on Day 2 (P = 0.03), while Day 1 values were not significantly different from Day 2 or Day 3 values (Fig. 3.2). Net HR was higher when subjects walked at 90 than at 75 (P = 0.0003) or 60% FWS (P = 0.004). There was no significant difference between 60 and 75% FWS. Between-day reliability was high (R, Table 3.4). Intra-subject, between-day variability was also high, but lowest when subjects walked at 75% FWS and highest when they walked at 60% FWS. (CV, Table 3.4).

3.5 Discussion

To the best of the authors' knowledge, this is the first study to examine the effect of repeated, multi-day, multi-speed, treadmill sessions on physiologic variables in children and adolescents with mild CP. The authors' hypothesized that there would be no between-day differences when subjects walked on the treadmill at a relatively slow speed, but that at faster speeds their physiologic strain would be lower on Day 2 and Day 3 compared to Day 1. When subjects walked at the fastest speed (90% FWS) there was a decrease from Day 1 to Day 3 in net $\dot{V}_E$ (3.6 l·minute^{-1}, Fig. 3.1) and net HR (8 beat·minute^{-1}, Fig. 3.2), thereby partly confirming our hypothesis that between-day differences would be found at the faster speed but not at the slower speeds. With the exception of net HR (where there was only a trend for this same pattern at 60% FWS, Fig. 3.2), there were no other significant differences from Day 1 to Day 3 in any variable, at any speed.

The present study had adequate statistical power (.80) to detect minimum between-day differences in net $\dot{V}_E$ at any speed of about 3.5 l·minute^{-1}. Fig. 3.1 shows there is no reduction in net $\dot{V}_E$ over successive days that was missed due to low statistical power. Our failure to find a significant difference in net $\dot{V}_E$ between 75 and 90% FWS independent of day, however, is likely due to low statistical power. There was adequate power to determine minimum between-speed differences of about 9.9 l·minute^{-1} and the difference in this case was 8.3 l·minute^{-1}. We found a reduction in the net $\dot{V}_E$ with repeated treadmill walks at a relatively high speed, but not at the lower speeds. In the absence of a similar pattern in $\dot{V}O_2$, this suggests that at the higher exercise intensity (90% FWS), $\dot{V}_E$ and $\dot{V}O_2$ were no longer tightly coupled, perhaps because the subjects were working above their ventilatory threshold. Since the subjects did not perform a progressive exercise test to peak $\dot{V}O_2$, however, ventilatory threshold can not be accurately determined for these subjects. We previously reported a similar

finding with this population (15). The group mean net $\dot{V}_E$ in the present study (Fig. 3.1) was similar to that of the subjects in this previous study (net $\dot{V}_E$ at 90% FWS = 22 l·minute^{-1}).

The study had adequate statistical power (.80) to detect minimum between-day differences in net HR at any speed of about 5 beat·minute^{-1}. Fig. 3.2 shows that no new between-day patterns in HR were missed. Had statistical power been higher, it would have been more clearly shown that when subjects walked at 90% FWS, net HR decreased with each visit (day) and when they walked at 60% FWS, net HR was lower on Day 3 compared to both Day 1 and Day 2. Our failure to find a significant difference in net HR between 60 and 75% FWS independent of testing day, however, is likely due to low statistical power. There was adequate power to determine minimum between-speed differences of about 11 beat·minute^{-1} and the difference in this case was 8 beat·minute^{-1}. We found net HR was reduced with repeated treadmill walks on different days at 90% FWS (and with a trend for the same finding at 60% FWS). While not specifically measured in this study, and in the absence of a similar pattern for the $\dot{V}O_2$ variables, it is possible that anxiety (due to walking relatively fast and relatively slow), which can increase HR (10,13), may have decreased over time as subjects became more familiar with treadmill walking without holding on to the handrails and with the testing environment and procedures. Although subjects were introduced to all equipment and procedures during the introductory visit, anxiety-related increases in HR can not be ruled out. It is possible that anxiety during treadmill walking is relevant to HR with this population, who have difficulty walking, and not to healthy children where this phenomenon is not observed (8,31). Furthermore, the extent of walking impairment appears to affect HR more than $\dot{V}O_2$ in this population, which again suggests that factors other than exercise intensity elevate HR in those with CP. Compared to the present group (Fig. 3.2), while walking at the same relative intensity (90% FWS), children and adolescents with CP who have more difficulty walking (lower walking-related

gross motor function scores and slower ground walking speeds than the present group) demonstrated 51% higher net HR, but only 13% higher net $\dot{V}O_2$-kg (15). In the future, a measure of anxiety could prove useful to more clearly determine the cause of the between-day differences in HR. It is possible that more practice time walking on the treadmill is needed to reduce anxiety-related between-day differences in HR.

We had adequate statistical power (.80) to detect minimum between-day differences in net $\dot{V}O_2$-kg at any speed of about 1.2 $ml \cdot kg^{-1} \cdot minute^{-1}$, which was the difference between Day 3 and Day 2, independent of speed. With a larger sample, the 1.1 ml $kg^{-1}min^{-1}$ increase from Day 1 to Day 2, irrespective of speed would likely have also been significant. Our failure to find a significant difference in net $\dot{V}O_2$-kg between 60 and 75% FWS, independent of testing day is probably due to low statistical power, as there was adequate power to determine a minimum between-speed differences of about 4.4 $ml \cdot kg^{-1} \cdot minute^{-1}$ and the difference in this case was 1.2 $ml \cdot kg^{-1} \cdot minute^{-1}$. It is difficult to determine from the results of the present study why net $\dot{V}O_2$-kg was higher on Day 2. Subjects may have walked differently on Day 2 (and hence were less economical) than on Day 1 or Day 3, although a *post-hoc* analysis of stride data (not shown) revealed no significant differences in stride length or rate among the three days. The between-day differences in net $\dot{V}O_2$-kg are small, however, compared to the differences among subjects and thus between-day reliability is high (Table 3.4). A previous treadmill walking study with 6 yr old healthy children (28) showed that, following 5 minutes of treadmill walking practice, within-day net $\dot{V}O_2$-kg was higher for the first than for the second and third trial. In this previous study, however, only one speed was used (1.34 $m \cdot s^{-1}$), which was about 30% faster than the group mean speed for 90% FWS (1.01 $m \cdot s^{-1}$). Thus, it is possible that we would have found speed-related differences in the pattern of the $\dot{V}O_2$ response to repeated treadmill walks had subjects been able to walk at a faster speed and therefore at a higher absolute exercise intensity. In other words, more

practice time may be needed for very, very mild subjects with CP who, like young healthy children, have an immature gait pattern, but are able to walk faster than the present subjects with CP. When 6-15 yr old children with mild spastic hemiplegic CP walked at 0.67 $m \cdot s^{-1}$, the same speed as the group mean speed for our slowest speed, for example, there were no within-day differences in net $\dot{V}O_2$-kg, which also suggests that a clear reduction in net $\dot{V}O_2$ with repeated treadmill walks is not seen with slower speeds in CP. When subjects walked on the treadmill at 90% FWS, mean net $\dot{V}O_2$-kg for the group (Table 3.3) was similar to that reported in the literature (16-21 $ml \cdot kg^{-1} \cdot minute^{-1}$) for children and adolescents with mild CP (15,30).

Post-hoc sample size calculations for the other metabolic variables, $\dot{V}O_2$ -stride and EE, showed the same results as for $\dot{V}O_2$-kg, *i.e.,* the sample of 8 subjects was sufficient to detect the main between-day difference (higher values on Day 2 than on Day 3 with no difference between Day 1 and Day 3, Table 3.3). As with $\dot{V}O_2$-kg, it is likely that there was insufficient power to detect the speed-related differences that were not significant (Table 3.3). Net $\dot{V}O_2$-stride showed the same pattern as net $\dot{V}O_2$-kg, possibly because there were no significant between-day differences in stride rate (not shown). We expected that stride rates would decrease over repeated walks on the treadmill as subjects became more familiar with treadmill walking and were able to take longer steps, but this was not the case. Our subjects, like healthy children (8), did not show any between-day differences in stride rate. EE showed the same pattern as $\dot{V}O_2$-kg, possibly because there were no significant inter-day differences in RER (not shown). We attempted to control fuel source somewhat by having the subjects fast (with the exception of water) for 2 h prior to coming to the lab (no caffeine for the preceding 3 h). We also tested each subject at the same time of day for the three visits. The last meal before testing, according to the information given to us by the subject or parent, was usually similar in content from testing day to testing day.

Between-day differences in all physiologic variables, were relatively small compared to the inter-subject differences and thus between-day reliability of all variables, irrespective of speed, was high, with the exception of RR, where reliability was moderate (Table 3.4). In other words, day to day intra-subject differences in these measures (with the exception of RR) have minimal effect on the ability of these measures to reliably differentiate between subjects. Our between-day reliability (Table 3.4) for net $\dot{V}O_2$-kg was greater than the within-day reliability reported in the literature (0.78) for children and adolescents with spastic hemiplegic CP (11). This is perhaps because our subjects received more walking practice (12-15 minutes compared to 5 minutes). It is also possible that the subjects themselves were more similar to each other in the previous study (all had hemiplegic CP) and thus, compared to the present study, between-trial differences in $\dot{V}O_2$ were relatively greater than the between-subject differences.

Intra-subject, between-day variability was less for the metabolic variables at 90% FWS than at the slower speeds (Table 3.4). In a clinical setting, where $\dot{V}O_2$ during treadmill walking might be tested for an individual before and after an intervention, it would perhaps be prudent to test such individuals at close to their fastest treadmill walking speed, rather than at slower speeds, especially if the expected difference in $\dot{V}O_2$ due to the intervention might be small. Net $\dot{V}_E$ showed higher intra-subject, between-day variability than the $\dot{V}O_2$-related measures. (Table 3.4). It may not be the most suitable physiologic outcome measure in a clinical setting. Although net HR and net RR both showed higher intra-subject, between-day variability than the other measures, this is mostly a "mathematical artifact" due to low values for both net HR and net RR. When absolute HR and RR are considered, the CV is much lower (about 4% for HR and 9-10% for RR, across the three speeds). Our mean intra-subject variability for net $\dot{V}O_2$-kg during treadmill walking was similar to that reported in the literature for this population (8.4 ± 8.5%) (11). Our mean intra-subject variability for absolute $\dot{V}O_2$-kg, 5.7-8.1%, is lower than what is reported for over ground

walking (4) (17% when speed is not controlled for, 13% when speed is controlled for and $\dot{V}O_2$ is calculated per m walked). The higher variability for over ground walking may reflect the greater motor impairment of the subjects in that study in that some of them used braces and walking aids. It is also possible that with speed (and the width of the walking track) more precisely controlled with treadmill walking, subjects' walk more similarly from trial to trial on the treadmill than over ground. If this is true, then a treadmill walking protocol might be more appropriate than an over ground one for assessment of an intervention, especially if small, but clinically relevant differences are expected. Further research is needed to determine if physiologic responses during treadmill walking are more reliable and less variable than during over ground walking in those with mild CP.

Only 81% of individual trials reached the steady state criteria in this study, which is similar to that (82%) reported for healthy children (8). It is difficult to say, but possible, that inter-individual variability was increased due to difficulties with achieving steady state in 19% of the trials. Previous research, however, has shown that group $\dot{V}O_2$ values are not significantly different between minute 2, 3 or 4 during treadmill walking in this population (30). It is also possible that patterns in the data were obscured due to the subjects having resting measures taken only on Day 1. We elected to have only one resting measurement session for each subject to decrease the time commitment for subjects (this study was part of a larger study and subjects were making a total of 7 visits to the lab, 3 after this phase of the study was complete). We also elected to have only one resting measurement session to decrease the between-day variability in the net physiologic measures due to the increased susceptibility of anxiety-related differences in resting measures. Since our RER measures were not different among the days, it is likely that there were no between-day differences in $\dot{V}O_2$ due to fuel or diet differences and thus the resting metabolic measures, if not affected by factors such as anxiety, would not have differed greatly among the testing days.

It is difficult to determine from our results or from the literature what the optimum protocol is to ensure that subjects with CP are habituated to treadmill walking. It appears that as little as 5 minutes of treadmill walking practice is needed to obtain reliable $\dot{V}O_2$ data if the walking speed is slow (11). Based on our results, after 12-15 minutes of walking practice, reliable and stable metabolic data may be obtained at various speeds. Both comfortable and fast ground walking speeds (Table 3.2) were, however, on average faster for the group than any of the treadmill walking speeds. The fastest treadmill speed (90% FWS) was closest to the comfortable ground walking speed (mean intra-subject difference = 0.25 ± 0.47 $m \cdot s^{-1}$). It has previously been shown that the comfortable walking speed on the treadmill is slower than the comfortable walking speed on the ground for children with mild spastic hemiplegic CP (9). The subjects in the previous study received a similar amount of treadmill walking practice to the present subjects. Thus, perhaps more practice would result in increases in the comfortable and fastest walking speeds on the treadmill and therefore decrease the differences between the comfortable and fast walking speeds on the ground and treadmill.

In conclusion, this is the first study to examine in children and adolescents with mild spastic CP, the effect on physiologic responses of repeated treadmill walks on different days, and whether the effects are different at different speeds. Irrespective of speed, in this sample, net metabolic responses on Day 1 did not differ from those on Day 3. Net $\dot{V}_E$ and net HR were both lower on Day 3 compared to Day 1, but only when subjects walked at the fastest speed (90% FWS). Since metabolic responses did not show the same pattern as these cardio-respiratory responses, it is possible that the reduction over time in net HR was due to a reduction in anxiety rather than an improvement in walking economy *per se* and the reductions in net $\dot{V}_E$, to an uncoupling of $\dot{V}O_2$ and $\dot{V}_E$. Thus these two variables may not be the most appropriate to measure if researchers wish to use a faster walking speed and only 12-15 minutes of

treadmill walking practice. Researchers interested in mechanisms and interventions related to walking economy in subjects with mild spastic CP may be able to obtain reliable net physiologic and stable net metabolic variables, especially those related to $\dot{V}O_2$, following one treadmill walking practice session. More research is needed to determine if physiologic responses during treadmill walking are more reliable and less variable than during over ground walking in those with mild CP. More research is also needed to determine the optimal treadmill walking habituation protocol in this population and whether more treadmill walking practice would result in greater similarity between comfortable and fast walking speeds on the ground and on the treadmill. A larger sample of subjects with mild CP, which includes subjects who walk faster and slower than the present group, would also increase the generalizability of our findings, which at present likely relate best to those whose walking speeds are similar to the present group.

3.6 Acknowledgements

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Table 3.1. Age, gender, maturity and anthropometric characteristics.

Subject	Age yr	Gender	Tanner Stage	Body Mass kg	Arm Span cm	Sum of 4 skinfolds mm
1	10.3	M	3	23.12	127.0	22.2
2	10.6	M	3	26.58	143.0	20.8
3	14.7	M	5	40.95	162.0	31.6
4	11.4	F	2	26.95	134.5	40.0
5	13.7	F	3	37.58	154.0	27.0
6	15.7	M	5	64.72	171.0	79.2
7	9.2	F	3	40.38	138.5	85.2
8	9.7	M	1	38.86	144.0	80.2
Mean	11.9			37.4	146.8	48.3
SD	2.5			13.1	14.7	28.2

Table 3. 2. Descriptors of cerebral palsy and gross motor function characteristics.

Subject	Topographic Distribution of Spasticity	Lower limb spasticity (MAS)		Severity (GMFCS)	GMFM%	CGWS $m \cdot s^{-1}$	FGWS $m \cdot s^{-1}$
1	Diplegia	*#R=1+	#L=1+	I	97.2	1.3	1.5
2	Diplegia	R=1+	L=1+	I	97.2	1.4	2.1
3	Diplegia	*R=1+	#L=1+	II	54.2	1.1	1.5
4	R hemiplegia	*#R=1+	L=0	I	95.8	1.3	1.7
5	Diplegia	*#R=1+	*#L=1+	II	79.2	1.2	1.4
6	R hemiplegia	*R=1+	L=0	I	97.2	1.0	2.1
7	R hemiplegia	#R=1+	L=0	I	97.2	1.2	1.7
8	Diplegia	*R=1+	*#L=1+	I	93.1	1.3	1.8
Mean					88.9	1.2	1.7
SD					15.3	0.12	0.26

* hamstrings muscle group = 2; #gastrocnemius muscle = 2

MAS = Modified Ashworth Scale. GMFCS = Gross Motor Function Classification System. GMFM = Gross motor function measure score for Dimension E (Walking, Running, and Jumping). CGWS = Comfortable ground walking speed. FGWS = Fast ground walking speed. R = Right. L = Left

Table 3.3. The effect of repeated treadmill walks on physiologic variables.

	60% FWS			75% FWS			90% FWS		
Variable	D1	D2	D3	D1	D2	D3	D1	D2	D3
Net $\dot{V}O_2$-kg $ml \cdot kg^{-1} \cdot min^{-1}$	11.2	11.8*	11.0	12.7	14.5*	13.1	18.4##	19.4*##	17.9##
	(1.9)	(2.2)	(1.6)	(2.0)	(2.4)	(2.3)	(2.7)	(2.9)	(2.6)
Net $\dot{V}O_2$-stride $ml \cdot stride^{-1}$	8.3	8.7*	7.7	8.7	9.6*	8.9	11.8##	12.0*##	10.8##
	(1.7)	(1.7)	(1.4)	(2.0)	(1.9)	(2.0)	(2.6)	(2.4)	(2.1)
Net EE $kJ \cdot min^{-1}$	9.2	10.1*	9.0	10.8	12.3*	11.3	16.2#	16.8*#	15.3#
	(2.1)	(2.6)	(2.0)	(2.7)	(3.0)	(2.9)	(4.4)	(4.4)	(3.8)
Net RR $breath \cdot min^{-1}$	10	13	12	14	16	16	24##	20##	19##
	(2.3)	(3.5)	(1.9)	(2.6)	(2.7)	(3.1)	(3.7)	(3.6)	(2.9)

*D3 < D2 ($P < 0.05$). #90% FWS > 60% FWS ($P < 0.05$). ##90% FWS > 60, 75% FWS (main effect for speed, $P < 0.05$). FWS = Fastest walking speed. D = Day. RR = Respiratory rate. EE = Energy expenditure. Group means (SEM) shown

Table 3. 4. Between-day reliability and intra-subject variability of physiologic variables.

		CV, %		
Variable	R	**60 % FWS**	**75 % FWS**	**90 % FWS**
Net Vo2-kg, $ml \cdot kg^{-1} \cdot min^{-1}$	0.96	10.1 (4.3)	12.7 (10.4)	7.6 (3.0)
Net $\dot{V}O_2$-stride, $ml \cdot stride^{-1}$	0.97	11.4 (5.0)	12.3 (10.5)	8.4 (2.4)
Net EE, $kJ \cdot min^{-1}$	0.98	10.2 (4.1)	12.6 (10.2)	7.6 (2.5)
Net $\dot{V}_E$, $l \cdot min^{-1}$	0.96	14.7 (6.3)	14.1 (8.5)	13.6 (7.1)
Net RR, $breath \cdot min^{-1}$	0.75	23.2 (18.9)	24.1 (23.4)	23.4 (23.3)
Net HR, $beat \cdot min^{-1}$	0.95	19.0 (11.8)	15.9 (16.3)	18.3 (29.3)

R = Intraclass correlation coefficient. CV = intra-subject coefficient of variation. Mean (SD) shown.

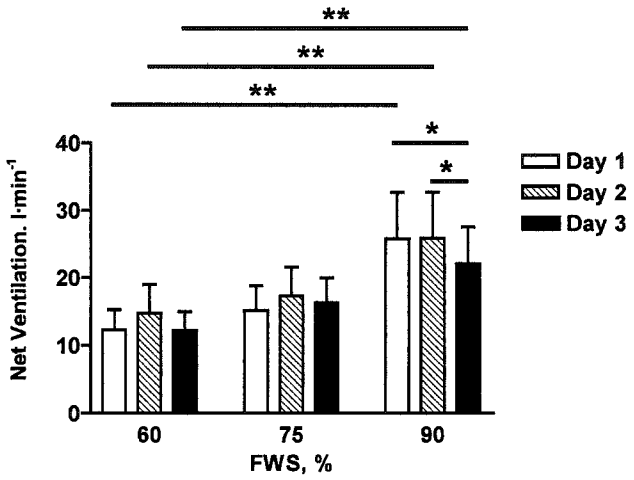

Figure 3.1. The effect of repeated treadmill walks on net ventilation.

*Day 3 < Day 1 (P = 0.04) and Day 2 (P = 0.03); ** 90% FWS > 60% FWS (P = 0.01), irrespective of day. FWS= Fastest walking speed. Group means (SEM).

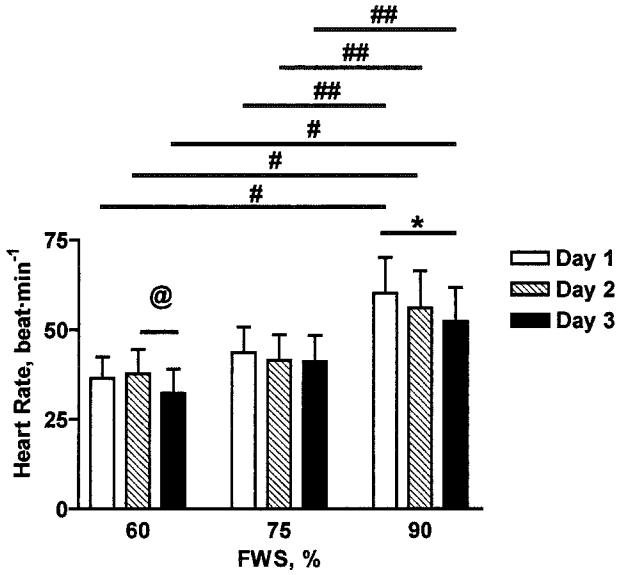

Figure 3.2. The effect of repeated treadmill walks on net heart rate.

*Day 3 < Day 1 (P = 0.0004); @ Day 3 < Day 2 (P = 0.03); #90% FWS > 60% FWS (P = 0.0004), irrespective of day; ##90% FWS > 75% FWS (P = 0.004), irrespective of day. FWS= Fastest walking speed. Group means (SEM).

CHAPTER 4: MINUTE-BY-MINUTE DIFFERENCES IN CO-ACTIVATION DURING TREADMILL WALKING IN CEREBRAL PALSY

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4.1 Abstract

The primary purpose of this study was to determine, in children and adolescents with mild spastic cerebral palsy (CP): i) minute-by-minute differences in lower limb antagonist muscle co-activation and stride length (SL) during treadmill walking following 12-15 minutes of treadmill walking practice, and ii) if the minute-by-minute pattern of co-activation is affected by site (thigh or lower leg) and lower limb dominance. A secondary purpose was to determine if overall there is a difference in co-activation between the dominant and non-dominant lower limbs. Eight independently ambulatory children and adolescents with mild spastic CP (9.2-15.7 yr) participated in the study. Minute-by-minute lower limb antagonist muscle co-activation and SL were measured during a 3-minute treadmill walk at 90% of individually determined fastest treadmill walking speed. Non-dominant thigh (quadriceps, hamstring muscles) co-activation decreased between minute 1 and a) minute 2 (6%), b) minute 3 (7.2%). Co-activation for the dominant lower leg (tibialis anterior, triceps surae muscles) decreased between minute 1 and minute 3 (11.3%). Non-dominant thigh co-activation was on average 27.3% higher than for the dominant thigh. Thigh co-activation was on average 27.7% higher than for the lower leg, independent of dominance or time. SL increased between minute 1 and minute 3 by 2.1%. Twelve to 15 minutes of

treadmill walking practice may be sufficient time to obtain stable co-activation and SL values by minute 2 of a fast treadmill walk. Dominance and site affect the magnitude of co-activation

4.2 Introduction

Cerebral palsy (CP) is a "group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising early in development" (25). It occurs 2 to 2.5 times per 1000 live births (28), with the most common subtypes being spastic diplegia and hemiplegia (28). Compared to typically developing children and adolescents, those with CP have a higher metabolic cost of walking (5, 34), which, it has been suggested (2), might be one of the causes of their early fatigability (7). Increased lower limb co-activation, defined here as concurrent electromyographic (EMG) activity in antagonist muscles, at both the thigh and lower leg, is associated with this high metabolic cost (34).

A treadmill walking protocol is often used by researchers interested in mechanisms, including co-activation, related to the increased metabolic cost of walking in CP (30, 32, 34) and in determining whether interventions reduce this cost (7, 18, 20). To ensure data from a treadmill walking protocol do not simply reflect changes due to increased skill walking on a treadmill, subjects should be habituated to walking on the treadmill prior to testing (33). Following about 15 minutes of treadmill walking practice, children and adolescents with CP walking for 4 minutes on the treadmill at 0.83 m s^{-1} showed no differences in oxygen uptake ($\dot{V}O_2$) between minute 2 and minute 3 or minute 4 (34). A more recent study (19) using similar subjects and 12-15 minutes of treadmill walking practice also showed that steady state $\dot{V}O_2$ (third minute) on day 1 was not different than on day 2 or day 3, independent of speed (subjects in this latter study walked at 60, 75 and 90% of their previously determined fastest treadmill walking speed (FWS)). From a metabolic perspective, 12-15 minutes of treadmill

walking practice appears sufficient time for habituation and 2-3 minutes, sufficient time to reach stable values within a walk. It is unknown, however, whether such a protocol would allow subjects with CP to obtain stable co-activation within a treadmill walk. It is also unknown whether the pattern of habituation is affected by co-activation site (thigh or lower leg) or lower limb dominance. In men with 1 minute of treadmill walking practice, the variability in the normalized (mean of gait cycle) EMG linear envelopes from the triceps surae muscle group reached its minimum level by 2 minutes of treadmill walking (comfortable speed) (13). The variability in the EMG linear envelopes from the tibialis anterior muscle in these subjects, however, did not show any pattern of habituation, even after 12 minutes of treadmill walking. Lower limb dominance did not affect the pattern of habituation for either muscle (13).

From a mechanical perspective, co-activation, especially during gait, is a means of increasing joint stiffness and reducing agonist force production (9). The greater co-activation at the lower leg (tibialis anterior, soleus muscles), compared to the thigh (vastus lateralis, hamstring muscles) seen with both typically developing children and adolescents and those with CP (35), for example, may reflect the greater requirement for stiffness at the ankle compared to the knee during gait. Although these *intra-lower* limb differences in co-activation have been found, it is unknown whether *inter-lower* limb differences exist. Since the increased co-activation in those with CP is attributed to central nervous system damage (17), it also seems likely that between the two legs, co-activation would be greater on the more involved, non-dominant lower limb, i.e., the side that presumably is non-dominant because it exhibits more motor damage. Information on inter-limb differences in co-activation would be useful to researchers and clinicians interested in motor control in those with CP and in the effects of interventions designed to improve motor control.

Finally, it is unknown how much treadmill walking practice is needed for those with CP before stride characteristics become stable. Data from healthy

adult women showed that stride to stride variability (stride time) was reduced over the first 7 minutes of treadmill walking practice, but not after that point (15-minute walk) (6). In a subsequent study with adult males, these researchers also found that following 60 minutes of treadmill walking practice, subjects still required 2 minutes of treadmill walking during a trial (independent of speed) before stable stride time values were seen (36). Following 15-20 s of treadmill walking practice, typically developing 7-11 yr old children walking and running on the treadmill at several different speeds showed no within-day or between day differences in stride length (SL), as measured during the final minute of a 6-minute walk (11).

While these EMG and stride studies suggest that it might be advantageous to have subjects with CP practice treadmill walking for well over 15 minutes and to have each walk last at least 7 minutes, this is unlikely to be feasible due to the time demands of such protocols and the risk of fatigue. Since treadmill protocols with those with CP are frequently used in studies where metabolic data are measured (7, 18, 20, 30, 32, 34), it seems prudent to investigate co-activation and SL using a protocol that has been shown to yield stable metabolic data, i.e., 12-15 minutes of walking practice preceding a 3-minute test.

The primary purpose of this study was to determine, in children and adolescents with mild spastic CP: i) minute-by-minute differences in lower limb antagonist muscle co-activation and SL during a 3-minute treadmill walk following 12-15 minutes of treadmill walking practice, and ii) if the minute-by-minute pattern of co-activation is affected by site (thigh or lower leg) and lower limb dominance. A secondary purpose of the study was to determine if overall there is a difference in co-activation between the dominant and non-dominant lower limbs. It was hypothesized that, following 12-15 minutes of treadmill walking practice; stable lower limb co-activation values would be established by the second minute of a 3-minute treadmill walk. It was also hypothesized that,

independent of time and site, co-activation would be greater for the non-dominant compared to the dominant lower limb and that independent of dominance or time, lower leg co-activation would be greater than for the thigh.

4.3 Methods

Subjects. The subject characteristics are summarized in Table 4.1. No subjects had previous experience walking on a treadmill without holding on to the handrails, although six subjects walked on a treadmill 1-2 times per week during their physical therapy sessions while holding on to the handrails. No subject had orthopedic surgery or had taken medication to reduce spasticity within the preceding year. All in the group had at least 105° of hip flexion and lacked no more than 20° of hip extension. The hamstring contractures (knee extension limitation with the hip flexed to 90°) were on average 35°. Ankle dorsiflexion (knee extended) was at least neutral (0°), bilaterally. The subjects did not have any medical conditions except CP and engaged in at least 2 h per week of physical activity outside of school hours. Written, informed consent was obtained from subjects at or over the age of 14 yr. For subjects under 14 yr, written, informed consent was obtained from parents preceded by assent from the child. The McMaster University Research Ethics Board approved the study. Subjects were recruited through a local pediatric rehabilitation center.

Design. The participants visited the Children's Exercise and Nutrition Centre on two occasions, as described below. There was a maximum of 2 weeks between the two visits.

Measurements. Visit 1: The subjects completed physical activity (modified from Bar-Or (2)) and health status questionnaires with parental assistance if required. Pubertal stage according to the criteria of Tanner (31) (pubic hair for boys, breast development for girls) was self-determined based on photographs (21). Since not all subjects could stand erect, arm span was used to estimate stature. The medians of three skinfold measurements taken at the biceps, triceps, subscapular and suprailliac sites on the dominant side were

summed and used as an estimate of body fatness. Body mass was measured (Mott Electronic Scale UMC1000, accuracy ± 10 g; Ancaster Scale Co. Ltd., Brantford, Canada) after subjects emptied their bladder. To calculate nude body weight, clothes, including shoes, were also weighed (Acculab 1200, accuracy ± 0.1 g; Acculab Sartorius Group, Edgewood, NY). The participants wore gym shorts, a T-shirt, socks and running shoes, with the same shoes worn for both visits. The topographic distribution of spasticity was based on the classification of Minear (24). One person (DM) determined the severity of gross motor involvement using the Gross Motor Function Classification System (26), a five-level grading system, where Level I refers to those with the mildest involvement. Spasticity was measured using the five level (0 = no spasticity; 4 = rigidity) modified Ashworth Scale (3). Lower limb passive range of motion (to screen for contractures) was assessed by goniometry using standardized techniques modified from McDowell et al. (22). Gross motor function related to walking was measured using the Walking, Running, and Jumping dimension of the Gross Motor Function Measure (27). Comfortable and fast over ground walking speed was measured over a 30 m walk way using the median of a triplicate measurement. To avoid the influence of fatigue on over ground walking speed, subjects rested in the sitting position between each trial until heart rate (HR) (Polar Vantage XL, Polar CIC, Port Washington, New York) was within 10% of its pre-exercise value. Upper limb dominance was determined by preferred hand for writing and preferred arm for throwing a ball. Lower limb dominance was determined by preferred foot for hopping and kicking a ball. Subjects were taught to walk on a recently calibrated treadmill (Woodway Desmo M Tread Erogometer; Woodway USA, Waukesha, WI) without holding on to the handrails. Each person's FWS on the treadmill (the fastest speed maintained for 3 minutes without loss of double limb support) was determined over three, 3-minute stages. Starting speed was the subject's self-selected comfortable treadmill walking speed. Total treadmill walking practice time was 12-15 minutes.

Visit 2: Subjects walked on the treadmill for 3 minutes at 90% FWS (1.01 ±0.54 m s^{-1}) while wearing the HR monitor, EMG surface electrode preamplifiers (gain 375, Motion Control Preamps, Iomed Inc., Salt Lake City, UT) and custom made footswitches (total weight of all equipment = 1491.4 g). EMG was monitored for the entire 3-minute treadmill walk at the thigh from the quadriceps and the hamstring muscle groups, and at the lower leg, from the tibialis anterior muscle and the triceps surae muscle groups. The surface electrodes were affixed at the largest part of the respective muscle belly at each site using standard electrode collars following appropriate skin preparation (abrading, cleaning with alcohol and shaving if necessary). The eight leads from the pre-amplifiers were plugged into a small, lightweight junction box attached to the back of the subject by an elasticized belt. A single cable from the junction box connected the subject to the main amplifiers (2, four channel amplifiers, Model 1700, A-M Systems, Carlsborg, WA) which in turn connected to the A/D data acquisition system of the PC computer (DATAQ Instruments Inc., Akron, OH). The overall EMG gain was set to 3400 with the gain for the quadriceps increased to 4X that of the others because of low amplitudes. The signals were bandpass filtered (10-500 Hz, ± 40 db/decade) and notch filtered at 60 Hz by the main amplifiers. The eight EMG signals were sampled at 1000 Hz per channel and stored on disk. Switches for each foot, were positioned and taped in place on the sole of the shoe at the heel and 1^{st}, 3^{rd} and 5^{th} metatarsal heads. The four leads from each foot converged into a single cable, which plugged into a second small junction box attached to the subject's elastic belt. A single cable from this junction box connected the subject to the A/D data acquisition system. Foot switch data were also sampled at 1000 Hz, simultaneously with EMG data. The absence of marked cross talk for the EMG channels was verified visually immediately prior to the treadmill walk using the functional and manual resistance methods for testing cross talk between antagonist muscles recommended by Winter et al. (37).

Calculations and Data Reduction. Using custom software written by one of the authors (MRP), the raw EMG signal from each site monitored was full-wave rectified and low-pass filtered off-line at 2.88 Hz to render linear envelopes. Identification of gait cycles (initial contact to initial contact of the right foot) was determined from footswitch data. All gait cycles beyond 3 SD of the mean cycle length for that trial were considered atypical and were discarded. The linear envelope for each muscle, for each gait cycle within a walk, were re-sampled to give 51, equidistant data points (bins), each representing 2% of the gait cycle, with one point representing 0%. The amplitude of the linear envelope value at each bin was normalized to a percentage of peak (100%) linear envelope amplitude within that gait cycle, a modification of the methods of Yang and Winter (38). An ensemble average linear envelope for each muscle within a trial was created by calculating the mean linear envelope value for all gait cycles within that trial at each of the 51 bins. Co-activation between antagonist muscles (thigh = quadriceps and hamstrings; lower leg = tibialis anterior and triceps surae) within the gait cycle was determined in the following manner. At each of the 51 bins within the cycle, the lower of the two antagonist ensemble averaged linear envelope values was considered to represent the co-activation value at that bin. The co-activation measure (CM), a unitless value (12) was the mean value across the 51 bins (10, 12, 34, 35). Figure 4.1 depicts one subject's CM for the dominant lower leg. This method to quantify co-activation was used because it relates to the metabolic cost of walking (10, 12, 34, 35). The metabolic cost of walking is of clinical relevance to this population and is sensitive to the effects of interventions (7, 18, 20). Other co-activation quantification methods used in gait studies: i) are largely descriptive, simply measuring the amount of time antagonist muscles are co-active (16), ii) are not related to the metabolic cost of walking (14), iii) require specialized calibration (8, 9) which is not always feasible for those with CP (35), iv) require extra equipment on the subject during walking (4), which the authors of this present study found in pilot work limited greatly the

number of subjects with mild CP who could perform the tests, or v) use non-normalized EMG data (15). The use of non-normalized EMG data assumes that factors that influence EMG data, are similar within and between subjects, an assumption which is likely not true for those with CP. It is unlikely, for example, that body composition is similar among the present subjects given the relatively large variability about the group mean for the sum of 4 skinfolds (48.3 ± 28.2). In addition, there is evidence to suggest that, at least for those with hemiplegic CP, body composition may not be the same on the affected and unaffected side (29). Normalizing data as in the present study, however, has also been criticized because this method does not account for the differing levels of muscle weakness that is typically found between antagonist muscle "pairs" in spastic conditions (8, 15). It has been argued (8, 15) that if one muscle or muscle group is much weaker than its antagonist, then co-activation could be artificially inflated if EMG amplitude data are normalized as suggested by Yang and Winter (38). Clearly an optimal method for quantifying co-activation during gait in children and adolescents with CP has yet to be found.

Statistical Analysis. There was a 3.1% data loss (failure of one EMG channel, the non-dominant triceps surae for one subject). To avoid an unbalanced design, an unbiased mean (the grand mean of all the CM values) was used as an estimate for the missing data. The effects on the CM of treadmill walking time (minute 1, minute 2, minute 3), co-activation site (thigh, lower leg) and lower limb dominance were analyzed using a 3-way, repeated measures ANOVA. All interactions (time x site; time x dominance; dominance x site; time x site x dominance) were also tested. A 1-way repeated measures ANOVA was used to analyze the effect of treadmill walking time on SL. Differences between any two pairs of interest were assessed *post-hoc*, using Tukey's HSD method. The 95% confidence intervals around significant differences were also calculated. Alpha was set at .01. Statistical analyses were done with Statistica software, Version 5.5 (StatSoft Inc, Tulsa, OK).

4.4 Results

Lower Limb Antagonist Muscle Co-activation. Since the three-way interaction (time x site x dominance) was significant (P = .003), the results are discussed at that level and only physiologically relevant pairs are compared. For the group, CM for the non-dominant thigh decreased between minute 1 and minute 2 by 2.17 (±1.56, 95% CI; P= .0097) and between minute 1 and minute 3 by 2.61 (±1.47, 95% CI; P = .002) (Figure 4.2A). For each minute of the walk, the mean CM of the group for the non-dominant thigh was higher than for the dominant thigh (mean difference = 7.49 ± 2.51, 95% CI, P = .0002) (Figure 4.2B). The group mean CM for the dominant lower leg decreased between minute 1 and minute 3 by 2.87 (± 1.45, 95% CI; P = .0008) (Figure 4.3). There were no significant differences in CM between the dominant and non-dominant lower legs at any minute of the walk (Figure 4.3). CM for the thigh was greater than for the lower leg on both the dominant and non-dominant sides at minute 1, minute 2 and minute 3 (mean difference = 6.72 ± 4.02, 95% CI; P > .003) (Figure 4.4).

Stride Length. Mean SL (m) ± SEM for minute 1, minute 2 and minute 3 were 1.06 ±0.13; 1.08 ±0.13 and 1.09 ±0.13, respectively. There was a significant increase in SL over time, but only between minute 1 and minute 3 (mean difference = 0.02 m ± 0.01, 95% CI; P = .004).

4.5 Discussion

The main finding was that 12- 15 minutes of treadmill walking practice was sufficient time to obtain stable CM and SL by minute 2 of a fast treadmill walk. Thus a protocol similar to that which yields stable metabolic data in this population (19, 34) also yields stable lower limb antagonist muscle co-activation and SL. It was also found that: i) the CM for the thigh on the non-dominant side was greater than on the dominant side at each minute of the walk, and ii) thigh CM was greater than lower leg CM on both the dominant and non-dominant sides throughout the walk.

The hypothesis that following 12-15 minutes of treadmill walking practice, stable lower limb antagonist co-activation values would be established by the second minute of a 3-minute treadmill walk was confirmed in that there were no significant differences in the CM between minute 2 and minute 3 on either side for the thigh or the lower leg. Visual examination of the patterns for the CM (Figures 4.2-4.4) suggests that one of the minute-by-minute differences in the CM could have been missed due to low statistical power. This is between minute 2 and minute 3 for the dominant lower leg (Figure 4.3). *Post-hoc* sample size analysis suggests that with eight subjects and a power of .80 (alpha = .01), differences of 1.26 (5%) may be detected. The actual difference was 1.01 (4%). Thus it is possible that a plateau was not reached after 2 minutes for the dominant lower leg. Such a finding would be in keeping with previous data for healthy adult males where the variability in the EMG linear envelopes from the tibialis anterior muscle did not show any pattern of habituation, even after 12 minutes of treadmill walking (13). A study with a larger sample size is required to determine if minute-by-minute differences were missed due to low statistical power.

The present results do not clearly show why CM decreased over time only for the non-dominant thigh and dominant lower leg. It is well known that proprioception from the lower leg is used to modulate local (at the ankle) antagonist muscle postural control responses (but not necessarily responses more proximally) (1). Muscle-lengthening surgery at the lower leg could, presumably, affect local proprioception and thus modulation of lower limb co-activation. Inter-subject differences in surgical interventions, however, do not appear to explain the present findings. Although four of the subjects had orthopedic surgery to correct muscle force imbalances at the ankle (tendo-achilles lengthening, three on the non-dominant side, one bilaterally), on examining individual data (not shown), we found that only two subjects showed a clear change in non-dominant lower leg co-activation. Both subjects had

hemiplegic CP and neither subject had a prior tendo-achilles lengthening. Optimally, we would have liked to recruit subjects who had not had previous orthopedic surgery, but this would not be indicative of the population in our area. Rather than inter-subject surgical differences, intra-site (thigh, lower leg) differences in motor control may explain the findings. Unnithan et al. (34), who studied a group of children and adolescents with CP similar to the present group, were unable to obtain a maximum voluntary contraction for the ankle plantar and dorsiflexors, but were able to do so for the quadriceps and hamstring muscle groups. This suggests that motor impairment in CP may be greater at the lower leg than at the thigh. If this is so, then the lack of minute-by-minute changes in co-activation at the most impaired of the site tested, that is, at the non-dominant lower leg, may reflect the inability of the central nervous system to modulate to any great extent the phasic activity of these muscles in response to habituation to treadmill walking. Monitoring of EMG activity throughout the treadmill-training period is needed to test this hypothesis. At the thigh, only the more motor-control impaired non-dominant side showed a reduction in CM over time. In this case, the least impaired site, the dominant thigh, may have habituated to treadmill walking during the 12-15-minute training period. Although, to the best of our knowledge, patterns of habituation have not been assessed in the quadriceps and hamstring muscle groups in typical (able-bodied) individuals, the phasic patterns of certain lower limb muscles (triceps surae) do stabilize quickly, within 2 minutes (13). Again, monitoring of EMG activity throughout the treadmill-training period is needed to determine if this is so (co-activation stabilizing quickly) for the dominant thigh in those with CP.

The hypothesis that, independent of time, co-activation would be higher for the non-dominant compared to the dominant lower limb was confirmed for the thigh, but not for the lower leg. The CM for the thigh appears to discriminate between the more involved and less involved (or non-involved) sides as determined by the lower limb dominance tests. Co-activation is elevated in CP

due to the central nervous system damage (17). As expected, co-activation was greater on the side with the greater impairment, that is, the non-dominant side. The finding of a higher CM at the non-dominant thigh compared to the dominant thigh may be contrary to the finding of Keefer et al. (14), who found no significant differences in thigh co-activation between the affected and non-affected side during treadmill walking in subjects with mild hemiplegic CP. It is possible that the difference in the distribution of spasticity between the present subjects (hemiplegic and diplegic) and the previous subjects (all hemiplegic) may explain this finding. However, of the three subjects with hemiplegia in the present study, only one had minimal differences between the two legs for co-activation at the thigh (1% higher on the dominant side). For the other two subjects with hemiplegia the difference in CM between the thighs was more marked (71% and 140% higher, respectively, on the non-dominant side). The difference in findings between the two studies is probably due to the differences in the method of quantifying co-activation. The co-activation index used in the previous study is a modification of that of Falconer and Winter (9). Interestingly, unlike the CM in the present study, which has also been shown to have a positive linear relationship with the metabolic cost of walking (34), Keefer et al. failed to find a significant linear relationship between their co-activation index and the metabolic cost of walking. Thus the present CM appears to be sensitive to lower limb dominance (at the thigh) and to the metabolic cost of walking, whereas the co-activation index used by Keefer et al. does not appear sensitive to these factors.

It is not clear why, for the more impaired (relative to the thighs) lower legs, the CM did not discriminate between the dominant and non-dominant sides. Since the CM values of the lower legs were significantly less than at the thighs, it may be that the CM must reach a threshold value before it can discriminate based on dominance, or perhaps more time is actually required for habituation before inter-limb differences are seen for the CM for the more involved lower legs. Between-day testing would be useful in determining whether the lower leg

CM is affected by repeated treadmill walks on different days. Visual examination of the data suggests that at minute 3, a difference in CM between the dominant and non-dominant lower leg could have been missed. However in this case, a pattern was not seen because of the inter-subject variability in responses. Five subjects showed the expected higher value on the non-dominant side, but three subjects showed the opposite pattern. The finding of a higher CM at the thigh compared to the lower leg is contrary to our hypothesis. The actual values, however, do not completely contradict the literature. Our finding of a mean (averaged across both lower legs) CM of 24.3 is similar to the 27.0 for the right lower leg (during treadmill walking at the same relative speed, 90% FWS) reported by other authors (34, 35) who used the same CM as in the present study and whose subjects with CP were similar to those in the present study. While these other researchers reported lower values (16.26) at the thigh compared to the present study, this may be due to between-study differences in the quadriceps muscles monitored. These previous researchers monitored only the vastus lateralis muscle of the quadriceps, whereas in the present study, the global quadriceps muscle group (which included rectus femoris) was monitored. It is possible that there is more co-activation between the biarticular hamstrings and biarticular global quadriceps than between the monoarticular vastus lateralis and the biarticular hamstrings. This may reflect co-activation at the hip, which was not considered by the previous researchers who used a monoarticular quadriceps muscle. Rectus femoris, for example, is often active during a greater percentage of the gait cycle in CP than in typically developing children (23). Research comparing co-activation at the thigh with and without inclusion of the rectus femoris muscle for the quadriceps could possibly clarify the reason for the difference between these present findings and those in the literature (34, 35).

The hypothesis that following 12-15 minutes of treadmill walking practice, SL values would be stable by the second minute of a 3-minute walk was confirmed. These findings are in keeping with previous research with typically

developing children, where, following 15-20 s treadmill walking practice, 7-11 yr olds walking and running on the treadmill at several different speeds showed no within-day or between day differences in stride length (SL), as measured during the final minute of a 6-minute walk (11).

This present study can not answer questions about minute-by-minute differences in CM and SL of children and adolescents with CP who are naïve to treadmill walking, as most of the subjects had experience walking on the treadmill, albeit, while holding on to the handrails. However, this reflects the experience of the typical child and adolescent with CP in our area, as treadmills are frequently used locally for rehabilitation. In areas where this is not the case, more than 12-15 minutes of treadmill walking practice may be needed to ensure those with CP are habituated to walking on the treadmill. It remains to be determined whether the pattern of habituation would be different if the subjects walked at slower speeds. The speed of 90% FWS was chosen as it is presumably a difficult speed, being very close to a subject's maximum speed and subjects walking at this speed would therefore likely show a pattern of habituation over time. It is possible that less time would be needed to achieve stable CM and SL if the subjects walk at slower speeds. In addition, since neither EMG nor footswitch data were collected during the treadmill walking practice period, the full pattern of habituation, which may be especially relevant for the dominant thigh and non-dominant lower leg CM, can not be determined. Finally, it remains unknown whether repeated treadmill walks on different days would affect the pattern of CM and SL values.

In conclusion (and within the limitations of this study), for children and adolescents with mild CP, 12-15 minutes of treadmill walking practice may be sufficient time to obtain stable lower limb antagonist muscle co-activation and SL by minute 2 of a 3-minute fast treadmill walk. Lower limb dominance appears to affect co-activation, at each minute of the walk, but only at the thigh, where co-activation was found to be greater on the non-dominant side. Contrary to

previous reports, lower limb co-activation in this study was higher overall for the thigh than for the lower leg, which may be due to inclusion in this study of the rectus femoris muscle as part of the quadriceps muscle group. Further research, (preferably with a larger sample size than in the present study) is needed to determine: i) minute-by-minute differences in CM and SL for children and adolescents with CP who are truly naïve to treadmill walking, ii) the effects of different speeds on these minute-by-minute differences, iii) the optimum practice time and whether this is also dependent on the treadmill walking speed, iv) whether repeated treadmill walks on different days affect the pattern of CM and SL values, and v) whether inclusion of rectus femoris at the thigh affects co-activation differences between the thigh and lower leg.

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Table 4. 1. Subject characteristics

Subjects	5 boys, 3 girls	**GMFCS**	Level I, n=5, Level II, n=3
Age, yr	11.9 (2.5)	**Lower limb dominance**	Left, n=6, Right, n=2
Body Mass, kg	37.4 (13.1)	**Lower limb spasticity (MAS)**	Varied from 0 (uninvolved limbs of those with hemiplegia) to 1^{+}
Sum of 4 skinfolds, mm	48.3 (28.2)	**GMFM-E, %**	88.9 (15.3)
Arm Span, cm	146.8 (14.7)	**CWS, m s^{-1}**	1.2 (0.12)
Pubertal Status	Tanner 1 or 2, n=3 Tanner 3, n=4 Tanner 5, n=1	**FWS, m s^{-1}**	1.7 (0.26)
Topographic Distribution of Spasticity	Diplegia, n=5 Hemiplegia, n=3	**Surgical History**	SDR, n=1 TAL (bilateral), n=1 TAL (unilateral, NLL), n=3 HL (bilateral), n=2

GMFCS, Gross Motor Function Classification System; MAS, Modified Ashworth Scale; GMFM-E, Gross Motor Function Measure Dimension E (Walking, Running, and Jumping); CWS, comfortable walking speed (over ground); FWS, fast walking speed (over ground); SDR, selective dorsal rhizotomy; TAL, tendo-achilles lengthening; NLL, non-dominant lower limb; HL, hamstring lengthening; Mean (SD) listed for group data.

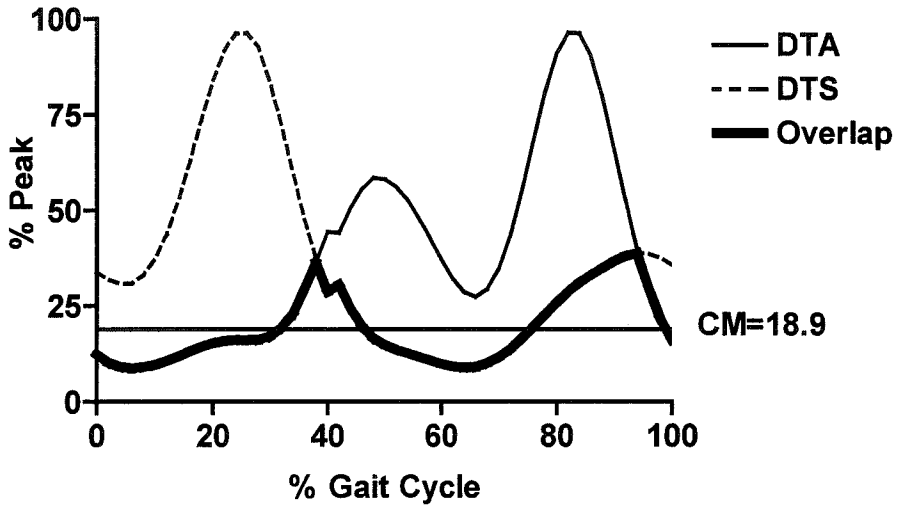

Figure 4.1. Co-activation measure for the dominant lower leg of one subject. The ensemble averaged linear envelopes (normalized to 100 % peak for each gait cycle) of antagonist muscles are overlapped. The mean value of the overlap curve yields the co-activation measure.

DTA, dominant tibialis anterior; DTS, dominant triceps surae; CM, co-activation measure.

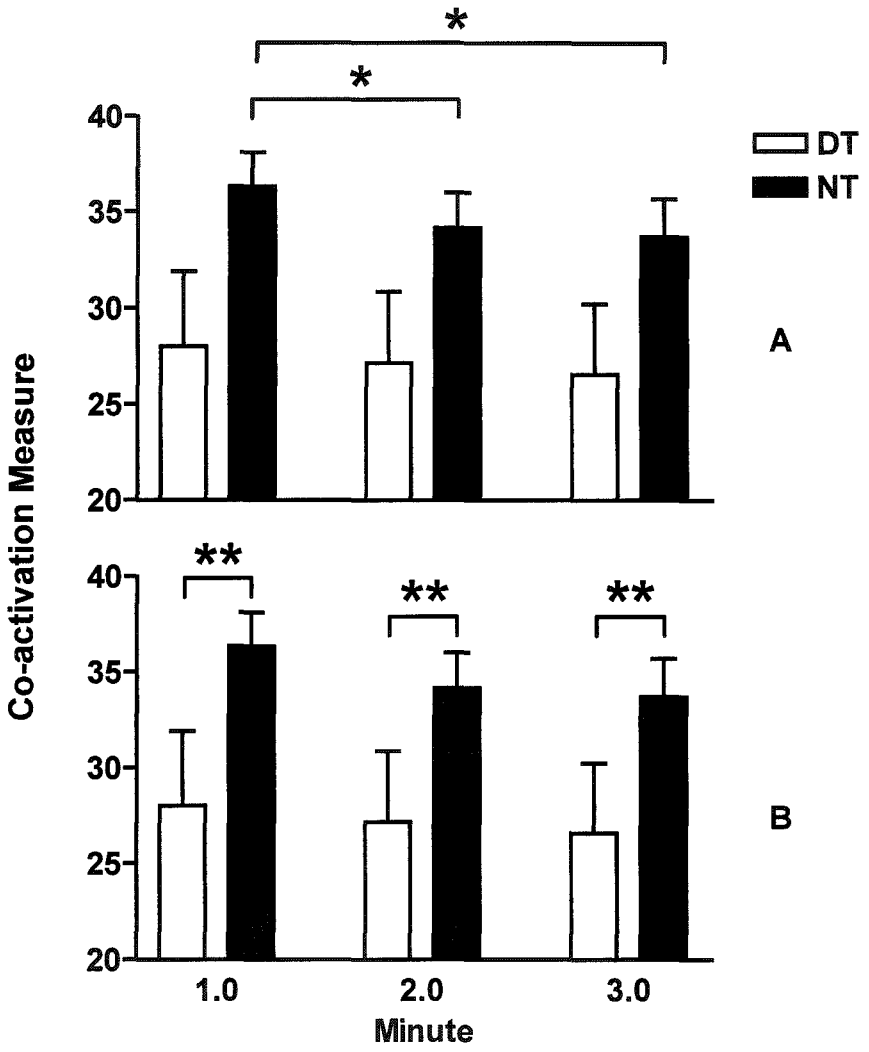

Figure 4.2. Co-activation measure for the dominant and non-dominant thigh for each minute of the 3-minute treadmill walk at 90% fastest walking speed.
A. Minute-by-minute differences. B. Intra-subject (dominant vs. non-dominant) differences.

* < minute 1 for non-dominant thigh; ** non-dominant thigh > dominant thigh.
DT, dominant thigh; NT, non-dominant thigh.
Mean and SEM, shown, P < .01.

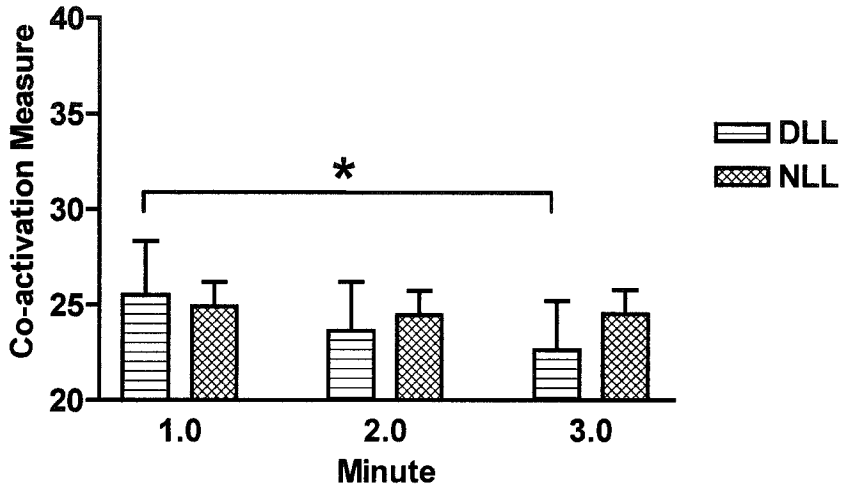

Figure 4.3. Co-activation measure for the dominant and non-dominant lower leg for each minute of the 3-minute walk at 90% fastest walking speed.

* < minute 1 for dominant lower leg.

DLL, dominant lower leg; NLL, non-dominant lower leg.

Mean and SEM, shown, $P < .01$.

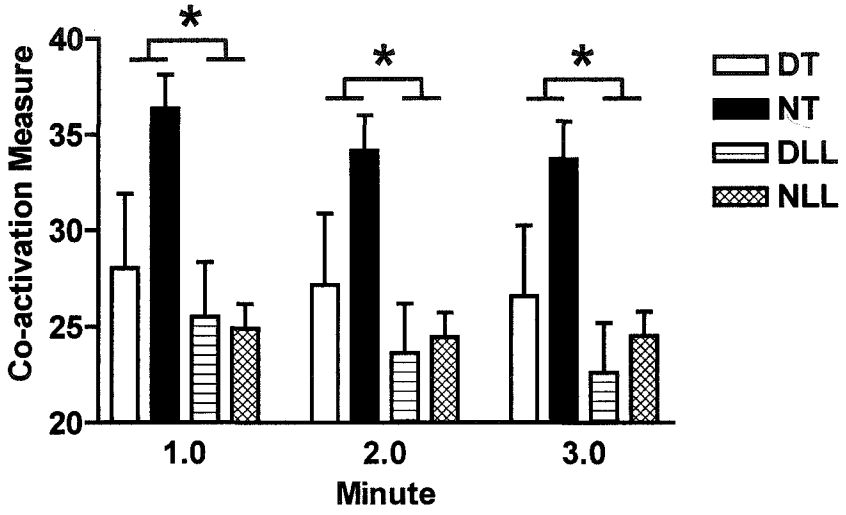

Figure 4.4. Co-activation measure for the thigh vs. the lower leg (dominant and non-dominant) for each minute of the 3-minute walk at 90% fastest walking speed.

* thigh > lower leg, independent of dominance.

DT, dominant thigh; NT, non-dominant thigh; DLL, dominant lower leg; NLL, non-dominant lower leg.

Mean and SEM, shown, $P < .01$.

CHAPTER 5: RESPONSES OF CHILDREN WITH CEREBRAL PALSY TO ARM-CRANK EXERCISE IN THE HEAT

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5.1 Abstract

Purpose: In response to passive heating, adults with hemispheric brain infarction demonstrate lower skin temperatures (T_{sk}) and higher sweating rates (SR) on the affected side. It is unknown if children with similar conditions demonstrate a similar response and if this response is advantageous to defending body temperature during exercise in the heat. The purpose of this study was to determine whether children with spastic cerebral palsy (CP) demonstrate less thermal strain than healthy peers during short (10 minutes each) bouts of arm cranking, a mode of exercise where metabolic rate can be matched between the two groups. Methods: Eleven young people (8.3-18.3 y) with spastic CP and 11 individually matched (body size, age and maturity) healthy controls (CON) performed 3x10-minute arm cranking bouts (40 rpm) in 35 °C, 50% RH. Body mass, metabolic and heart rate (HR) responses, and body temperatures were periodically measured. Individuals within each CP-CON pair worked at the same intensity (0.55 ±0.18 $W \cdot kg^{-1}$ body mass). Data were analyzed using a repeated measures ANOVA (alpha = 0.05). Results: Subjects with CP showed no difference from CON in metabolic and HR responses, or SR (as inferred from body mass changes corrected for fluid intake and output). There were also no differences between the groups in the rectal temperature change from room temperature (21-23 °C). The increase in T_{sk} from room temperature, however, was slightly (0.6 °C), but significantly lower ($P < 0.0001$; 95% CI = 0.5-0.7 °C) in

the subjects with CP compared to CON. Conclusion: Subjects with CP demonstrate thermal strain responses similar to CON during upper body exercise at relatively low intensities for short duration in a warm climate.

5.2 Introduction

When adults with hemispheric brain infarction are exposed to a heat stimulus at rest, the paretic side of the body compared to the non-paretic side shows increased sweating (5) and decreased skin temperature (6). Although it is unknown whether such atypical responses influence their ability to defend body temperature during exercise in a warm climate, any such responses could have a greater impact on children with such conditions compared to adults due to the children's higher body surface area (BSA)-to-body mass ratio. One of the more common pediatric conditions similar to adults with hemispheric brain infarction is spastic cerebral palsy (CP) (13). When performing lower body exercise children with CP, however, expend greater metabolic energy (and thus produce more metabolic heat) than do able-bodied children (2,21) due to increased lower limb antagonist muscle co-contraction (21) and excessive mechanical power production (22). Use of upper body exercise such as arm cranking could provide a means of matching their metabolic rate to that of able-bodied controls (CON). Such a design would allow for investigation of the effect of CP on body temperature responses to exercise in a warm climate independent of between-group differences in metabolic heat production.

We therefore hypothesized that during short duration arm-crank exercise of the same relative intensity in a warm, moderately humid climate, children and adolescents with CP compared to healthy CON individually matched for body size, age and maturity would demonstrate: i) similar metabolic heat production, ii) lower increases in rectal temperature (ΔT_{re}), iii) lower increases in mean skin temperature (ΔT_{sk}), iv) similar heart rate (HR), and v) greater evaporative sweat loss. To test these hypotheses, children and adolescents with mild spastic CP and matched, healthy CON performed 3x10-minute arm cranking exercise bouts

in 35 °C, 50% relative humidity (RH), a climate which is similar to a very warm summer day in Southern Ontario. We chose short duration exercise as it reflects our clinical experience with the patterns of physical activity in subjects with CP. Pilot work with such patients has also revealed that they were not able to consistently exercise with the upper body at a moderate intensity for a longer duration.

5.3 Methods

Eleven children and adolescents with spastic CP were individually matched to 11 healthy CON. The matching criteria were: age ±1 yr; body mass ±10%; arm span ±5%; biological maturity (Tanner Stage); gender; and race. Subject characteristics, including matching criteria are detailed in Table 5.1. Five additional volunteers with spastic CP and characteristics similar to those detailed in Table 5.1 did not complete the study. One boy and 1 girl dropped out after visit 1, due to family commitments (boy) and refusal of the rectal thermistor (girl). Three other girls did not complete the exercise protocol because they could not crank consistently.

Eight subjects in the CP group had a diplegic topographic distribution of spasticity; three had a hemiplegic distribution (based on Minear (11)). Seven subjects had mild CP, i.e., Level I or II on the Gross Motor Function Classification System (17), and 4 of them had moderate CP (Level III). Subjects were classified by one of the authors (DM), who is familiar with this classification system. No one in the CP group had orthopedic surgery within the preceding year. All subjects, CP and CON, were otherwise healthy, involved in 3-5 h per week of physical activity outside of school hours, and on no medication that would affect the variables measured in the study. The subjects also refrained from caffeine for 3 h, eating for 2 h, and from heavy exercise for 8 h before coming to the lab for both visits. The study was approved by the Ethics Review Board of the Faculty of Health Sciences, McMaster University. Subjects in the CP group were recruited through the local children's rehabilitation centre. The CON were recruited through

public advertisements. Before participation, written informed consent was obtained from a parent, or subject over 14 years, preceded by verbal assent from those children under 14.

Study design and structure. Subjects visited twice the laboratory at the Children's Exercise and Nutrition Centre. Visit 1 took place at 21-23 ±1°C during which time it was determined for each subject with CP, the power output that would yield a moderate intensity exercise (HR = 120 - 130 beat·minute^{-1}) that the subject could sustain for three bouts of 10 minutes. Visit 2 took place in a climatically-controlled chamber at 35 ±1°C, 45-50% RH with air motion < 0.2 m·s^{-1}. For the subjects with CP, in one case, the exercise intensity was lowered for the last two bouts, for two others it was increased. Each CP-CON pair, however, always exercised at the same intensity relative to body mass (W·kg^{-1} body mass), i.e., power output per kg was the same in each pair. Likewise, absolute exercise intensities were similar, since body mass was closely matched (mean inter- CP-CON pair difference = 0.6 kg). Each CP-CON pair was also tested during the same season and during the same time of day. Data collection took place over a 1-4 week period for each subject except for one subject whose second visit took place 6 weeks after the first due to scheduling problems. The minimum time between visits 1 and 2 was 4 days. Since testing took place during the same season for each CP-CON pair and since the CP-CON subjects were similar in physical activity levels, it was assumed there were no differences between the pairs in acclimatization to the chamber environment.

Protocols and measurements. *Visit 1 (21-23 °C)*: The subjects completed questionnaires about physical activity (modified from Bar-Or (1)), health status and diet (time, content and amount of the last meal and snack), with the assistance of a parent if needed. Pubertal stage (pubic hair for boys, breast development for girls) was self-determined, based on photographs (9) according to the criteria of Tanner (20). Total body length was estimated from arm span (Stanley metal tape measure, Canadian Tire Corp., Hamilton, ON, Canada)

because not all the CP group could stand erect. Relative body adiposity was estimated by summing the medians of three skinfold measurements taken at the biceps, triceps, subscapular and suprailliac sites on the non-dominant side. Body mass (Mott Electronic Scale, UMC1000, accuracy ±10 g; Ancaster Scale Co. Ltd., Brantford, ON Canada) was measured after subjects emptied their bladder. To subsequently calculate nude body weight, clothes, including shoes were also weighed (Accuba Scale, 1,200, accuracy ±0.1 g). Boys wore shorts, socks and athletic shoes. Girls wore the same with the addition of a bikini top.

For the arm cranking bouts, subjects were seated in an adjustable chair with a footrest. Hips, knees and ankles were fixed at 90° flexion. Straps at the chest, thighs and feet were used to maintain this position. The chair height and position were adjusted relative to the ergometer (a recently calibrated Fleisch Ergometer, Metabo, Epalinges, Switzerland) such that when the handle was furthest from the subject, the corresponding shoulder and elbow were flexed 80°-85° and 0°-5°, respectively; and when the crank arm was closest to the subject, the corresponding shoulder and elbow flexion were 0°-5° and 90°, respectively. This positioning remained consistent across all bouts during both visits for each individual. Subjects performed 3x10-minute arm cranking bouts (40 rpm), separated by 10-minute rest periods. A crank speed of 40 rpm was chosen based on pilot work (the subjects with CP were not able to consistently maintain a crank speed of 50 rpm). Heart rate (Polar Vantage XL, Polar CIC, Port Washington, New York) was continuously measured and stored as 5-s averages in the receiver. To accommodate the subjects to the mouth piece, subjects were connected to a metabolic cart (Vmax 29 Pulmonary Exercise System, SensorMedics Corp., Yorba Linda, CA, USA) which was calibrated just prior to data collection. Expired air was collected for 2 minutes of steady state (minutes 7 and 8) during each bout. Data were averaged over 20-s increments and the information was stored in the Vmax system's computer. These metabolic data were discarded.

Visit 2 (35 ±1°C, 45-50% RH): Health status and diet were confirmed with a short questionnaire as in visit 1. Diet was standardized by giving all subjects two slices of toasted bread (Wonder bread, no cholesterol) with jam (E.D. Smith, no sugar added) and 100 ml of water about 30 minutes before entering the chamber. Clothes and all equipment that the subject would wear during the session were weighed. Just prior to entering the chamber, subjects emptied their bladder and, with a parent's assistance if necessary, inserted a rectal thermistor (YSI 400 series, Yellow Springs Ohio) 8-10 cm beyond the anal sphincter to allow measurement of rectal temperature (T_{re}). Skin thermistors (YSI 400 Series, Yellow Springs Ohio) were affixed at the anterior mid-forearm (bilaterally), the distal one-third of the non-dominant anterior thigh; and at the anterior chest, 2-3 cm below the sternal notch using a thin, breathable adhesive film (Tegaderm, 3M. St. Paul Mn) just larger than the surface area of the thermister. Heart rate, T_{re} and skin temperatures (T_{sk}) (Doric bridge model 450, ±0.1°C) were measured at room temperature (21 – 23 °C) and recorded just prior to subjects entering the chamber. Body mass was measured and recorded upon entry into the chamber and during the first and 8th minute of each rest period. Rectal and skin temperatures were measured and recorded within the first minute in the chamber, the 5th and 10th minute of each exercise bout and during the 9th minute of the first and second rest periods. To maintain euhydration, children drank a predetermined amount of chilled water, 0.7% of their body mass (10), which was divided into three equal portions, with the first drink given upon entering the chamber, the second, after the first exercise bout, and the third, after the second exercise bout. If it was noted during the chamber session that the CP subject was gaining weight, to avoid hyperhydration, the final drink was not given. Each CP-CON pair drank the same amount of water relative to their body mass.

The exercise protocol in the chamber and the HR and expired gas measurements were as in visit 1. To allow for the measurement of recovery heart rate (HR_{rec}) all subjects also remained seated and refrained from moving or

speaking for 2 minutes after each exercise bout. The CP group worked at the intensity determined in visit 1. The CON subjects worked at the same relative intensity as their CP match. The mean power output was 0.55 ±0.18 $W \cdot kg^{-1}$. The chamber was maintained at 35 ±1°C, 45-50% RH. Immediately after leaving the chamber, subjects emptied their bladder and removed their clothes. Urine output and the clothes and equipment worn by the subject were weighed to allow for correction of fluid losses other than sweat and respiratory water loss (see "calculations and data reduction", below).

Calculations and data reduction. Metabolic heat production during each exercise bout was determined from the steady state $\dot{V}O_2$ of that bout, corrected for the total mechanical work done to move the flywheel. Steady state $\dot{V}O_2$ in $l \cdot kg^{-1} \cdot$(metabolic rate) was converted to units of energy expenditure, $kJ \cdot kg^{-1}$, using the following equation:

$\dot{V}O_2$, l (during analysis period) x (3.815 + 1.232 x RER)*x 4.186** (1)

* Regression equation created from the data of Lusk (7)

** Conversion factor for determining energy in kJ from energy measured in kcal

Steady state HR during exercise (HR_{ex}) was calculated from the average HR during the same analysis period as for $\dot{V}O_2$. The HR_{rec} for each exercise bout was determined as the difference between HR_{ex} and the average of the second minute following each exercise bout.

Mean T_{sk} was calculated as the sum of weighted local skin temperatures (0.4 chest temperature, 0.4 thigh temperature, 0.2 forearm temperature), a modification of the weightings of Hardy and Dubois (4). Since it was not practical with the subjects with CP to record from a greater number of skin sites (the subjects had limited patience during set up and also found more skin temperature thermistors distracting) we decided to limit the measurement to

three sites. To account for inter-subject differences in T_{re} and T_{sk} prior to entering the chamber, the change from room temperature (21-23 °C) in T_{re} (ΔT_{re}) and in T_{sk} (ΔT_{sk}) values were also calculated.

Whole body evaporative sweat loss was determined from the change in body mass (over the entire period in the chamber) corrected for water intake during the chamber session, urine output, respiratory water loss (12), and the change in the mass of the clothes and equipment. Evaporative sweat loss is reported relative to body surface area (3). Body mass changes were also determined after each bout. To determine if differences in clothing absorbency effected results, the amount of sweat retained in clothes was also calculated as the change in mass of the clothes over the time in the chamber.

Statistical analysis. Inter-group differences (each CP-CON pair) and change over time (for body temperatures) were assessed with a repeated measures ANOVA, general linear model type. The difference between any two means was assessed *post-hoc* using Tukey's HSD method. Differences between the groups (each CP-CON pair) for the sum of four skinfolds, body surface area, sweating rate and amount of sweat retained in the clothing were assessed with a paired t-test. All analyses were performed in Minitab for Windows, Release 13.1 (Minitab Inc., State College, PA), with alpha = 0.05.

5.4 Results

During arm-cranking exercise there were no significant differences between the CP-CON pairs in metabolic rate (for bouts 1, 2, 3 respectively, CP = 0.49 ±0.04, 0.48 ±0.05, 0.51 ±0.05 l·minute^{-1}, CON = 0.49 ±0.05, 0.50 ±0.05, 0.50 ±0.05 l·minute^{-1}), nor in total heat production (for bouts 1, 2, 3 respectively, CP = 88.6 ±7.9, 88.2 ±9.5, 93.9 ±8.7 kJ·kg^{-1}, CON = 88.5 ±9.0, 90.7 ±9.0, 90.6 ±9.9 kJ·kg^{-1}). There were also no significant inter-group (CP-CON pairs) differences in ΔT_{re}, nor were there differences between the groups in the pattern of ΔT_{re} over time in the chamber (Fig. 5.1). Figure 5.2 shows that the T_{re} responses for the individual pairs were, however, variable. The CP subjects, for

example were higher than their CON match through the session in four cases (01. 02, 03, 04), while in two cases (05, 11) the pattern of the T_{re} response changed over time, that is, the CON started out higher than CP with the differences between the pairs decreasing as the session progressed (Fig. 5.2). Although there was some inter-pair variation in ΔT_{sk} responses (not shown), as a group, the ΔT_{sk}, for the CP-CON pairs was on average 0.6 °C lower ($P < 0.0001$; 95% CI = 0.5-0.7 °C) in those with CP compared to the healthy children and adolescents (Fig. 5.3). For all subjects, the fastest rise in ΔT_{sk} occurred between the first and 10th minute in the chamber (mean=1.4 °C, 95% CI = 1.1 - 1.6 °C, $P < 0.0001$) (Fig. 5.3). There were no significant between-pair differences in sweat loss (CP = 171.5 ±14.7 $g \cdot m^{-2} \cdot h^{-1}$, CON = 167.4 ±13.7 $g \cdot m^{-2} \cdot h^{-1}$). Figure 5.4 shows that individual CP-CON pair differences in sweating rates were, however, variable. There were no CP-CON pair differences in body mass changes over each exercise bout (for bouts 1, 2, 3 respectively, CP = 0.05 ±0.02, -0.05 ±0.01, -0.06 ±0.01 kg, CON = 0.06 ±0.01, -0.04 ±0.1, -0.07 ±0.01 kg), nor in the amount of sweat remaining in the clothing after the chamber session (CP = 6.6 ±2.5 g; CON = 3.3 ±1.8 g). HR responses (HR_{ex}, HR_{rec}, Table 5.2) were also similar between each subject with CP and their able-bodied match.

5.5 Discussion

This is the first reported study to investigate thermal strain in children and adolescents with spastic CP. As expected, there were no differences between the CP and CON pairs in metabolic rate or heat production during arm cranking, thus the heat burden was similar in the two groups. This allowed us to identify whether any underlying thermal strain differences existed between the groups. The lack of no appreciable rise in ΔT_{re} beyond baseline in either group (Fig. 5.1), however should be taken with caution in light of the individual CP-CON T_{re} data shown in Figure 5.2. Ten minute exercise bouts appear to be too short to see meaningful changes in T_{re} in 7 of the 11 subjects with CP. The inter-group difference in ΔT_{sk}, 0.6 °C, although statistically significant, is physiologically and

clinically a very small difference. Moreover, any possible differences in cutaneous blood flow between the groups, for example, were not sufficient to provoke differences in cardiovascular strain between the groups, as there were no inter-group differences in HR_{ex} or HR_{rec} (Table 5.2). There was also no between-group difference in evaporative heat loss, as estimated by sweat loss (Table 5.2, Fig. 4). Furthermore, body mass changes during the exercise bouts were not different within the pairs. Absorbency of the clothing was also similar and thus did not affect the sweating response.

The lack of a difference in metabolic heat production between the groups is likely reflective of the relatively mild motor impairment in the upper limbs of most our subjects with CP in that eight of them had a topographic distribution where legs were more affected than arms. While there are no data, to the best of our knowledge, for arm cranking gross economy (the ratio between total mechanical work performed to move the fly wheel and the total metabolic energy expended during the work, %), in healthy children and adolescents, the mean values for the present CP (12.0 ±2.6%) and CON (12.2 ±1.6%) groups were similar to the reported values for gross arm cranking economy in healthy adults (13-14%) (18). A previous study (8) with a CP group who were somewhat more involved than the present group (less motor ability), however, showed lower arm cranking economy values (7.9-9.3%) than those reported here. Thus, it is possible that more severely affected subjects with CP (those with more upper limb spasticity or motor impairment) might have a higher metabolic heat production than able-bodied children during arm cranking in the chamber, perhaps due to excessive upper limb antagonist muscle co-contraction which is associated with spasticity in the upper limbs in those with CP (16). In the present study, however, we had to recruit less involved individuals because pilot testing revealed that those who were more involved were unable to arm crank consistently during the required exercise bouts.

Use of T_{re} as an estimate of body core temperature, is a limitation in this study. Changes (due to climatic and metabolic heat stress) in T_{re} lag behind changes in esophageal and tympanic and temperature (15). The changes in T_{re} reported here may therefore not have occurred fast enough to fully reflect transient changes in body core temperature during each 10-minute exercise bout. This is made evident in Figure 5.2, where T_{re} clearly increases in only 4 of the 11 subjects with CP. However, for ethical and comfort reasons, measurement of body core temperature at the esophagus, the preferred method (19), was not feasible. For several reasons we chose not to measure tympanic temperature. First, tympanic temperature, unlike T_{re}, is related to both skin and environmental temperature (14) and thus would have been at least somewhat influenced by the warm environmental conditions in this study. Second, it would have been difficult to periodically measure tympanic temperature during exercise, as the subjects with CP did not keep their heads still while arm cranking. Third, use of a tympanic temperature sensor that remained in the ear throughout the session would have been unacceptable to the subjects with CP due to the discomfort of this type of device.

The data from this study can not adequately explain why ΔT_{sk} was reduced in those with CP. More efficient evaporation of sweat could explain the findings, but this is likely not the case since there were no differences between the CP and CON in BSA and furthermore, unpublished photographic data from our lab on the forearm sweating pattern of 4 subjects with CP and 4 CON (matched as in the present study) showed no physiologically relevant inter-group differences in sweat drop area (CP = 0.026 mm^2, CON = 0.020 mm^2) or in % of skin covered by sweat (CP = 3.3%, CON = 3.1%). The failure to find a difference in HR likely reflects the similar abilities of both groups to defend body temperatures under the present conditions. It is unlikely that any inter-group differences in the measures of thermal strain were masked by differences between our groups in anthropometric variables or biological maturity since we

were successful in matching these characteristics (Table 5.1). Moreover, although we did not *a priori* match for the sum of 4 skinfolds or body surface area, these characteristics were also not significantly different between the groups (Table 5.1). The subjects were also similarly hydrated (loss of body fluid over the time in the chamber was 0.62 ±0.16 and 0.62 0.14 % body mass, for the CP and CON groups, respectively) and acclimated to the chamber conditions (as noted in Methods, above).

In conclusion, within the study limitations (variable thermal strain responses of the CP-CON pairs, inability of the subjects to exercise sufficiently long to detect consistent changes in T_{re}) no meaningful physiological differences were found between the subjects with CP and their matched CON. Therefore, mild-moderate CP does not appear to affect thermal or physiologic strain during short duration upper body exercise of moderate intensity in a warm climate, that is, under the conditions found in this study. It is unknown whether children with more severe CP would demonstrate similar responses. It is also unknown if differences between CP and CON subjects would be shown if an exercise modality could be found that could be tolerated longer or if the overall time in a warm climate was increased (more exercise bouts). In addition, the quantity of thermal strain encountered by these children when they engage in lower body exercise, where they do produce more metabolic heat than healthy controls, is also unknown.

5.6 Acknowledgements

We would like to thank the young people who participated in this study for their time and effort. We would also like to thank Dr. C. Goldsmith for assistance with the statistical analysis.

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Table 5.1. Subject characteristics. Mean (minimum-maximum) listed for characteristics 1-5. Frequencies listed for characteristics 6-8.

Variable	CP	CON
Age, yr	12.1 (8.3-18.3)	11.0 (8.3-14.7)
Body mass, kg	38.5 (21.6-60.7)	39.1 (19.4-60.1)
Sum of 4 skinfolds, mm	42.7 (21.8-83.2)	36.9 (23.2-81.6)
Arm span, cm	149.0 (125-179)	148.1 (129-169.5)
Body surface area, m^2	1.27 (0.83-1.64)	1.26 (0.97-1.70)
Pubertal stage	Tanner 1, n = 6	Tanner 1, n = 6
	Tanner 3, n = 1	Tanner 2, n = 1
	Tanner 5, n = 4	Tanner 4, n = 1
		Tanner 5, n = 3
Gender	Boys, n = 10	Boys, n = 10
	Girls, n = 1	Girls, n = 1
Race	Caucasian, n = 9	Caucasian, n = 9
	Black, n = 2	Black, n = 2

Although subjects were not *a priori* matched for the sum of 4 skinfolds and body surface area, there were no significant differences between the groups for these measures. CP = cerebral palsy; CON = control.

Table 5.2. Heart rate responses of the two groups in each of the exercise bouts.

Variable	CP			CON		
	Exercise Bout			Exercise Bout		
	1	2	3	1	2	3
HR_{ex}, beat·min^{-1}	121.6	124.3	124.1	122.6	123.7	124.0
	(1.9)	(1.6)	(1.9)	(4.3)	(4.1)	(4.3)
HR_{rec}, beat·min^{-1}	21.1	20.6	24.1	21.9	21.3	23.1
	(2.7)	(2.7)	(2.6)	(1.7)	(2.0)	(3.1)

Values are mean (SEM). CP = cerebral palsy; CON = control. HR_{ex} = heart rate during exercise; HR_{rec} = recovery heart rate

The HR_{rec} for each exercise bout was determined as the difference between HR_{ex} and the average of the second minute following each exercise bout. There were no significant differences between the CP and CON groups for any of the variables.

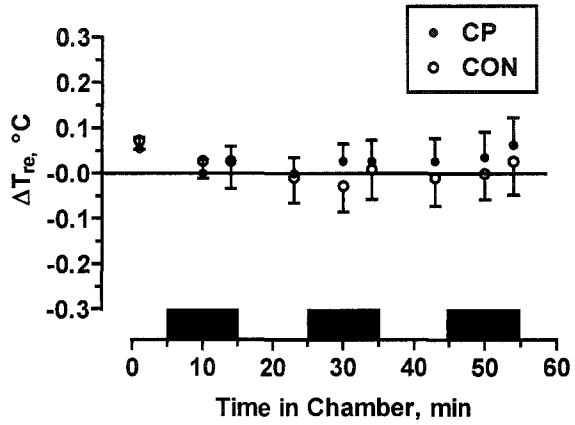

Figure 5.1. Change in rectal temperature (ΔT_{re}) during time in the chamber. There were no differences between the cerebral palsy (CP) and control (CON) groups, nor did time in the chamber affect the pattern. Group means and SEM. Line indicates T_{re} at room temperature (21-23 °C). Filled boxes indicate exercise periods.

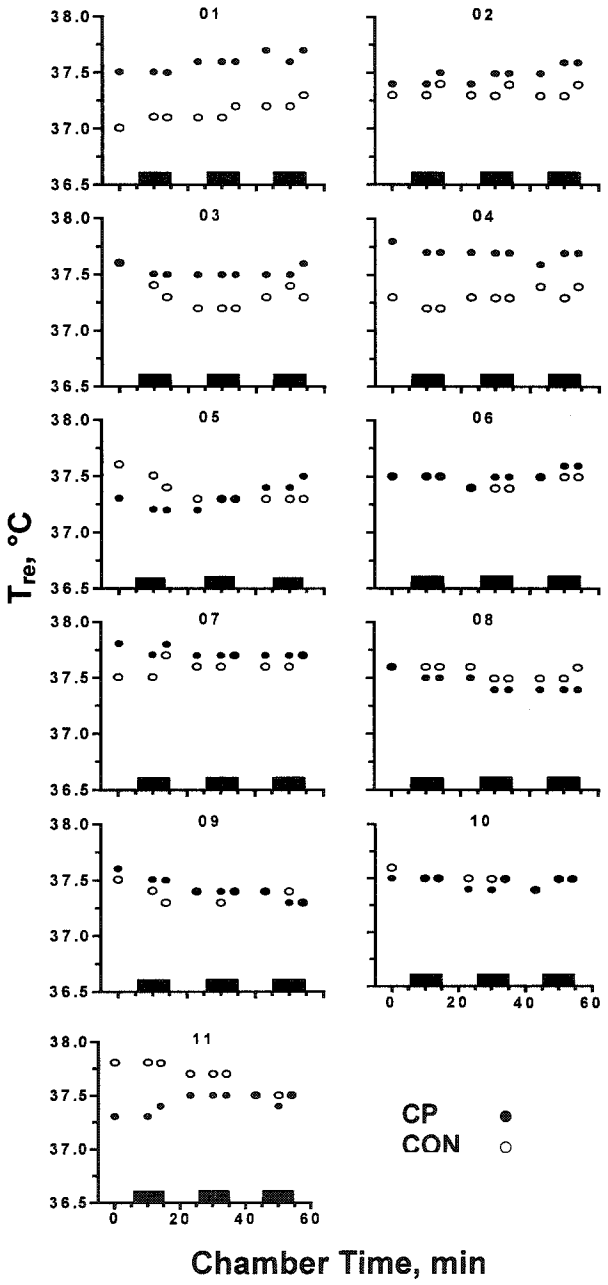

Figure 5.2. Rectal temperature (T_{re}) during time in the chamber for each cerebral palsy (CP)–control (CON) pair. Filled boxes indicate exercise periods. The exercise intensity was sufficient to induce an increase in T_{re} only in 4 of the 11 CP subjects (01. 02, 05, 11) and only one of the CON matches (01).

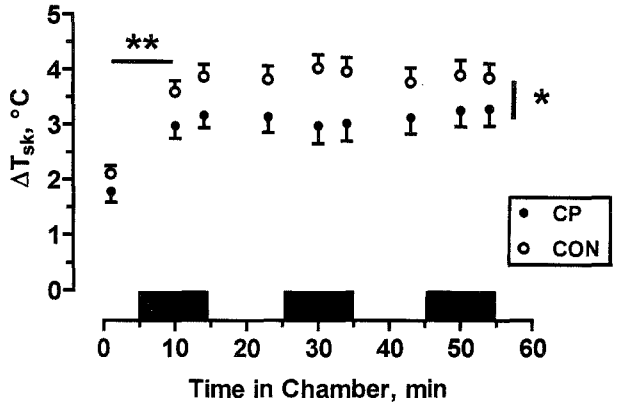

Figure 5.3. Change in mean skin temperature (ΔT_{sk}) during time in the chamber. Group means and SEM. Filled boxes indicate exercise periods.

*significant difference ($P<0.0001$) between the cerebral palsy (CP) and control (CON) groups independent of time in the chamber.

**significant difference ($P<0.0001$) between ΔT_{sk} at minute 1 and at minute 10 for both groups. See text for details.

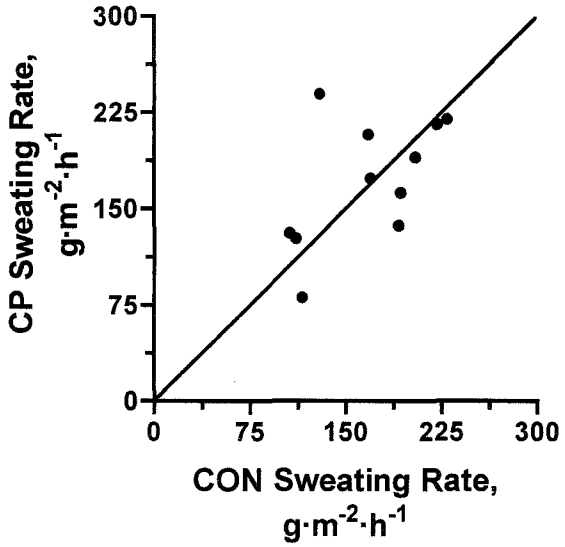

Figure 5.4. Individual sweating rate (SR) responses for the cerebral palsy (CP) and control (CON) pairs. The straight line indicates values for which SR would equal for a pair. There was individual variability in SR among the pairs with no significant difference between the pairs.

CHAPTER 6: RESPONSES OF CHILDREN WITH CEREBRAL PALSY TO TREADMILL WALKING EXERCISE IN THE HEAT

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6.1 Abstract

Purpose: When metabolic rate during arm-cranking in the heat is equated between children and adolescents with cerebral palsy (CP) and matched controls (CON), there are no relevant inter-group differences in heat strain. The metabolic rate, however, is known to be higher in CP during treadmill walking. The purpose of this study was to determine if during treadmill walking in the heat, the higher oxygen uptake ($\dot{V}O_2$), and thus greater metabolic heat production in those with CP would result in greater heat strain compared with able-bodied, matched CON. **Methods**: Ten boys and girls (10.3-16.3 y) with spastic CP and 10 individually matched (age, body size, biological maturity, gender, race) healthy CON performed 3x10-minute treadmill walking bouts in 35 °C, 50% RH. Body mass, metabolic variables, heart rate (HR), body temperatures and rating of perceived exertion (RPE) were periodically measured. Individuals within each CP-CON pair walked at the same speed and slope (0.9 ± 0.4 $m \cdot s^{-1}$, 3.3 ± 0.6%). **Results**: Steady state $\dot{V}O_2$ during walking, body temperatures, and HR were all higher in the CP group compared with CON. $\dot{V}O_2$ was on average 40% higher, rectal temperature was 0.4 °C (99% CI = 0.1-0.6 °C) higher and HR (during the final minute of each exercise bout) was 37 $beats \cdot minute^{-1}$ (99% CI = 19-56 $beats \cdot minute^{-1}$) higher. There were no differences between the

groups in sweating rate (as inferred from body mass changes corrected for fluid intake and output), or in RPE. **Conclusion**: The subjects with CP demonstrated greater thermal strain than CON during treadmill walking where they require more metabolic energy and thus produce more metabolic heat than CON.

6.2 Introduction

Compared with their able-bodied peers, the oxygen cost of walking in children and adolescents with cerebral palsy (CP) is up to 3 times greater (6,27). Even subjects with mild CP have been shown to expend 60% more metabolic energy as a group than healthy controls (CON) walking on the treadmill at the same speed ($0.83 m \cdot s^{-1}$) (27). Increased lower limb antagonist muscle co-activation (27) and increased mechanical power production (26) of the subjects with CP are both associated with their low walking economy. Children and adolescents with CP also rate their perceived exertion higher than healthy CON at a given exercise intensity (3). It is unknown, however, whether during walking exercise in the heat, the higher oxygen uptake ($\dot{V}O_2$), and thus greater metabolic heat production in children and adolescents with CP would result in greater heat strain compared with able-bodied CON. When metabolic rate is matched in CP and CON pairs (mild-moderate CP) during arm-cranking in the heat, there are no physiologically relevant differences between the pairs in thermoregulatory responses (14). For able-bodied boys exercising in a hot, dry environment, however, it has been suggested (8) that age-related differences in walking economy may explain the higher rectal temperatures (T_{re}), skin temperatures (T_{sk}), and heart rate (HR) of the younger compared with older subjects reported during treadmill walking ($1.56 m \cdot s^{-1}$) (29), but not during cycling (9). During walking on the treadmill, younger boys are less economical than older boys and hence produce more metabolic heat (10). During cycling, however, metabolic rates are similar between the groups (9). Should children and adolescents with CP not be able to adequately dissipate their increased heat production, this could put them at risk for heat-related illnesses. The population of those with CP for

whom this could be an issue would be those with mild CP since they are capable of working at higher intensities as they are not as limited by their motor deficit(s).

We therefore hypothesized that during short duration treadmill walking exercise at the same speed and slope in a warm, moderately humid climate, children and adolescents with mild, spastic CP, compared with healthy CON individually matched for age, body size, biological maturity, gender, and race, would demonstrate: i) higher metabolic rates, ii) greater increases in T_{re} (ΔT_{re}), iii) greater increases in mean T_{sk} (ΔT_{sk}), iv) a higher exercise heart rate (HR_{ex}), v) similar sweating rates, and vi) a higher rating of perceived exertion (RPE). To test these hypotheses, children and adolescents with mild, spastic CP and matched, healthy CON, walked 3x10 minutes in 35 °C, 50% relative humidity (RH), a climate that is similar to a very warm summer day in Southern Ontario. We chose exercise of short duration because it reflects our clinical experience with the patterns of physical activity in subjects with CP. Pilot work with this group has also revealed that they are not able to tolerate walking bouts of a longer duration in these environmental conditions.

6.3 Methods

Subjects. Ten children and adolescents with mild, spastic CP were individually matched (age ±1 yr; body mass ±10%; arm span ±5%; biological maturity (Tanner Stage); gender; and race) to 10 healthy CON (Tables 6.1 and 6.2). Two additional volunteers (one boy and one girl) with spastic CP and characteristics similar to those detailed in Tables 6.1 and 6.2 did not complete the study. Both dropped out after visit 1, due to refusal of the rectal thermistor. All subjects in the CP group were able to walk without support. No one in the CP group had undergone orthopedic surgery within the preceding year or taken medication to reduce spasticity within the preceding 6 months. The degree of soft tissue contracture was similar in all subjects with CP. They all had at least 100° of hip flexion and lacked no more than 20° of hip extension. Passive range of motion at the knee was full (tested with the hip extended) but the subjects on

average had about a 40° limitation (lack of knee extension with the hip at 90°) of the extensibility of the hamstring muscle group (bilaterally). Ankle dorsiflexion (knee extended) was at least neutral (0°). There were no lower limb soft tissue contractures in the CON subjects. All CON subjects were healthy and all CP subjects were healthy with the exception of their CP. The CP and CON subjects were involved in, on average, 1-2 h per week of physical activity outside of school hours, and not taking medication that would affect the variables measured in the study. While all study participants had prior experience with treadmill walking, with the exception of one subject with CP who walked on a treadmill weekly (7 minutes each time), no one had walked on a treadmill in the six months prior to the study. All participants refrained from caffeine for 3 h, eating for 2 h, and from heavy exercise for 8 h, before coming to the lab for both visits. The study was approved by the Ethics Review Boards of the Faculty of Health Sciences, McMaster University and the Bloorview MacMillan Children's Centre. Subjects in the CP group were recruited through local children's rehabilitation centres. Those in the CON group were recruited through public advertisements. Before participation, written informed consent was obtained from a parent, or subject over 14 years, preceded by verbal assent from those children under 14.

Study design and structure. Subjects visited the laboratory at the Children's Exercise and Nutrition Centre on two occasions. Visit 1 took place in room temperature (21-24 °C) conditions. During this visit we determined, for each subject with CP, the treadmill belt speed and slope that would yield a moderate intensity exercise (HR = 140-150 beats·minute^{-1}) that the subject could sustain for three bouts of 10 minutes. We did not chose a lower intensity exercise because our previous findings with lower intensity exercise in the heat in this population (14) showed no physiologically significant differences (in relevant physiologic variables) between the subjects with CP and CON. Pilot work also showed that not all the subjects with CP could sustain (for the three 10-minute bouts in the heat in Visit 2) an exercise intensity in thermoneutral higher than that

which we chose. We have previously reported a group mean maximum heart rate for these subjects (in thermoneutral conditions on the treadmill) of 189 beats minute^{-1} (12). A HR of 145 beats minute^{-1} is about 77% of maximal HR, which we define as moderate intensity exercise.

In visit 2 the climatically-controlled chamber was set at 35 ±1°C, 45-50% relative humidity (RH) with air motion < 0.2 m·s^{-1}. During this visit, four of the subjects with CP had their exercise intensity increased for the last two bouts to ensure they reached the desired intensity. Each CP-CON pair, however, always walked at the same speed and slope for each bout. One subject with CP, who walked without support over ground, was unable to do so on the treadmill, even after the treadmill (walking) teaching and habituation session. This subject held on to the treadmill handrail with one hand during the treadmill walks. One other subject, who likewise walked without support over ground, occasionally held on to the handrail with one hand during the treadmill walks. Since we could not control the amount of body weight supported by the upper limb, the CON matches for these two subjects did not hold on to the railing during their walks. The mean treadmill belt speed and slope were 0.9 ± 0.4 m·s^{-1} and 3.3 ± 0.6%, respectively. Each CP-CON pair was tested during the same season, and during the same time of day. Data collection took place within 1- 2 wk for each subject with the exception of one subject with CP who, due to scheduling issues, completed the study within a 16-day period. The minimum time between visits 1 and 2 was 2 days. Since testing took place during the same season for each CP-CON pair and since the CP-CON subjects were similar in physical activity levels, it was assumed that they were similarly acclimatized to the testing environmental conditions.

Protocols and Measurements. *Visit 1*: Subjects completed questionnaires about physical activity (modified from Bar-Or (2)), health status and diet (time, content and amount of the last meal and snack), with the assistance of a parent if needed. Pubertal stage (pubic hair for boys, breast

development for girls) was self-determined, based on photographs (15) according to the criteria of Tanner (25). Total body length was estimated from arm span since not all the subjects with CP could stand erect. Body adiposity was estimated by summing the medians of three skinfold measurements taken at the biceps, triceps, subscapular and suprailliac sites on the dominant side. Body mass (Mott Electronic Scale, UMC1000, accuracy ± 10 g; Ancaster Scale Co. Ltd., Brantford, ON Canada) was measured after subjects emptied their bladder. To subsequently calculate nude body weight, clothes, including shoes, were also weighed (Accuba Scale, 1,200, accuracy ± 0.1 g). Boys wore shorts, socks and athletic shoes. Girls wore the same with the addition of a bikini top. The same shoes were worn for both visits. Topographic distribution of spasticity was based on the classification of Minear (17). One person (DM) determined the severity of gross motor involvement using the Gross Motor Function Classification System (21), a five-level grading system, where Level I refers to those with the mildest involvement. The degree of lower limb spasticity was assessed using the modified Ashworth Scale (4), a five level scale (0 = no spasticity; 4 = rigidity) which is feasible and commonly used with the CP population (24). Lower limb passive range of motion (to screen for contractures) was assessed by goniometry using standardized techniques modified from McDowell et al. (16). Gross motor function related to walking was measured using the Walking, Running, and Jumping component of the Gross Motor Function Measure (22). Walking proficiency was also determined by measuring the comfortable walking speed on level ground (30 m walkway) using the median of a triplicate measurement. Subjects rested in the sitting position between each trial until HR (Polar Vantage XL, Polar CIC, Port Washington, New York) was within 10% of its pre-exercise value. Borg's 6–20 RPE scale (5) was then introduced and subjects were instructed in its use as previously described (2).

Participants were also familiarized with the equipment and taught to walk on the treadmill without using the handrails. They were then habituated to

walking on the treadmill (13). After resting for 10 minutes the subjects performed 3x10-minute treadmill walking bouts while HR was continuously measured and stored as 5-s averages in the receiver. The exercise bouts were separated by 10-minute rest periods. To accommodate the subjects to the mouthpiece, they were connected to a metabolic cart (Vmax 29 Pulmonary Exercise System, SensorMedics Corp., Yorba Linda, CA, USA) which was calibrated just prior to data collection. Expired air was collected for 6 minutes (minutes 4-9) during each bout. Expired gas data were averaged over 20-s increments and the information was stored in the Vmax system's computer. There was a one-minute break in each walking bout (after minute 3) to allow proper insertion of the mouthpiece. Pilot work showed us that most subjects with CP could not tolerate the mouthpiece for the entire 10 minutes of the three exercise bouts and they could not insert it properly while walking. During the last 20 s of the third minute and of the final minute of each walk subjects were asked to rate their perceived exertion using Borg's 6-20 RPE scale. These metabolic and RPE data were discarded.

The desired speed and slope was that which would yield (for the subjects with CP) a HR of 140 - 150 beats·minute^{-1}. The initial speed was each (CP) subject's comfortable treadmill walking speed, determined at the end of the treadmill habituation period. They walked at this speed for 2 minutes and then the treadmill speed was adjusted accordingly. A slope was added for those subjects who could not maintain a walking speed that yielded the target HR. In general, it took 4-6 minutes (2-3, 2-minute "steps") to reach the target HR in the CP group. Each CON walked at the same treadmill belt speed and slope as their CP match.

Visit 2: Health status and diet were confirmed with a short questionnaire as in visit 1. Diet was standardized by giving all subjects two slices of toasted bread (Wonder bread, no cholesterol) with jam (E.D. Smith, no sugar added). Subjects emptied their bladder and, with a parent's assistance if necessary, inserted a rectal thermistor (YSI 400 series, Yellow Springs, OH) 8-10 cm beyond

the anal sphincter to allow measurement of T_{re}. To measure T_{sk}, skin thermistors (Steri-Probe #499B, Cincinnati Sub-Zero Products, Inc. Cincinnati, OH) were affixed at the lateral mid-upper (dominant) arm, the distal one-third of the anterior thigh (dominant leg); and just posterior to the inferior angle of the scapula (dominant upper limb). Prior to entry to the climatic chamber, heart rate and body temperatures at rest (ante chamber, 21-24°C) were measured and recorded and clothing and the HR monitor were weighed. Body mass was measured and recorded upon the subjects' entry into the chamber and during the third and eighth minute of each rest period. Rectal and skin temperature were measured continuously during the subjects' time in the chamber and stored as one-minute averages in a data logger (Mini Logger, Series 2000, Mini Miter Co. Inc., Bend OR, ± 0.01°C), a light weight box (25 g) that was attached to the small of the back of each subject with a narrow elastic belt. The temperature data were later downloaded to a computer for subsequent analysis. Rectal temperature was monitored during the first and eighth minute of each rest period by connecting the rectal thermistor to a Doric bridge (model 450, ± 0.1°C). To maintain euhydration, subjects drank a predetermined amount of chilled (4 ± 1°C) water, 0.8% of their body mass, a modification (based of pilot data) of our previous work with subjects with CP arm cranking in the heat (14). The water was divided into three equal portions, with the first drink given upon entering the chamber, the second after the first exercise bout, and the third after the second exercise bout. If it was noted during the chamber session that the CP subject was gaining weight, to avoid hyperhydration, the final drink was not given. Each CP-CON pair drank the same amount of water relative to their body mass. The subjects were in the chamber for 68 minutes.

The exercise protocol in the chamber, and the HR, expired gas, and RPE measurements were as in visit 1. The CP group worked at the speed and slope determined in visit 1. The CON subjects worked at the same speed and slope as their CP match. Immediately after leaving the chamber, subjects emptied their

bladder and removed their clothes. Urine output and the clothes and equipment worn by the subject were weighed.

Calculations and Data Reduction. *Oxygen uptake* during each walk was determined from the steady state $\dot{V}O_2$ in l·minute^{-1} (the mean of minutes 5-9 of each exercise bout). This measure was used as an indirect estimate of metabolic heat production. *Cardiovascular strain* during treadmill walking in the heat, (HR_{ex}), was determined as the average HR during the last minute of each walk. *Body temperatures* during the time in the chamber (with the exception of peak T_{re}, see below) were extracted from the minute-by-minute body temperature data at 13 time points (the last minute of the pre exercise period and the fifth and 10th minute of each exercise bout and rest period). Mean T_{sk} was calculated as the sum of weighted local skin temperatures (0.4 trunk temperature, 0.4 thigh temperature, 0.2 upper arm temperature), a modification of the weightings of Hardy and Dubois (11). Since it was not practical with the subjects with CP to record from a greater number of skin sites (the subjects had limited patience during set up and also found more skin temperature thermistors distracting) we decided to limit the measurement to three sites. To account for inter-subject differences in T_{re} and T_{sk} prior to entering the chamber, the change from room temperature (21-24 °C) in T_{re} (ΔT_{re}) and in T_{sk} (ΔT_{sk}) was also calculated. Peak T_{re} was defined as the highest minute-by-minute value for each subject during his or her time in the chamber. *Sweating Rate* was calculated from the change in body mass (over the entire period in the chamber) corrected for water intake during the chamber session, urine output, respiratory water loss (18), and the change in the mass of the clothes and equipment. Sweating rate is reported relative to body surface area (7). The *rating of perceived exertion* was measured as the absolute rating the subject made on the Borg 6-20 RPE scale.

Statistical analysis. Inter-group differences (each CP-CON pair) and changes over time (for body temperatures) were assessed with a 2-way, repeated measures ANOVA. The difference between any two means was

assessed *post-hoc* using Tukey's HSD method. Differences between CP-CON pair members in the two groups for the sum of four skinfolds, body surface area and sweating rate were assessed with a paired t-test. All analyses were performed with Statistica for Windows (Version 5.5, StatSoft Inc, Tulsa, OK), with alpha = 0.01.

6.4 *Results*

Within the CP-CON pairs, independent of exercise bout, $\dot{V}O_2$ was significantly (P = .0006) higher in the CP subjects (for bouts 1, 2, 3 respectively, mean ±SEM, CP = 0.84 ±0.08, 0.88 ±0.11, 0.86 ±0.12 l·minute^{-1}; CON = 0.57 ±0.05, 0.62 ±0.07, 0.62 ±0.07 l·minute^{-1}). The mean difference between the groups was 0.26 l·minute^{-1} (99% CI = 0.10-0.42 l·minute^{-1}). The higher $\dot{V}O_2$ in the CP group was a consistent finding for all CP-CON pairs (Figure 6.1). From 32 minutes in the chamber onwards ΔT_{re} was also significantly (P<0.0002) greater for those subjects with CP compared with their CON match (Figure 6.2). By the end of the last exercise bout (minute 58) the difference between the group means in ΔT_{re} was 0.31 °C (99% CI = 0.1-0.5 °C). In addition, the subjects with CP started to show a significant (P<0.0008) increase in ΔT_{re} from 32 minutes in the chamber onwards, while this did not occur in the CON subjects until minute 58 (Figure 6.2). Peak T_{re}, was also significantly (P = .002) higher in those with CP (CP = 38.0 ±0.07 °C, CON = 37.6 ±0.07 °C; mean difference = 0.4 °C, 99% CI = 0.1-0.6 °C). Figure 6.3 shows that peak T_{re} was higher for the CP subjects in all but one of the CP-CON pairs. The ΔT_{sk} was significantly (P<0.0002) greater for the CP subjects compared with their CON matches from minute 11 in the chamber onwards (Figure 6.4). By the end of the last exercise bout (minute 58) the difference in ΔT_{sk} between the group means was 1.1 °C (99% CI = 0.4-1.9°C). Within the group of subjects with CP, by minute 11 the ΔT_{sk} was significantly (P<0.001) greater than during the pre-excise period in the chamber (Figure 6.4). The values for the CON group, however, did not

change from their initial level (Figure 6.4). Within the CP-CON pairs, independent of exercise bout, HR_{ex} was significantly (P = .0001) higher in the CP subjects (for bouts 1, 2, 3 respectively, CP = 143 ±3.8, 151 ±2.7, 155 ±3.4 beats·minute^{-1}; CON = 108 ±4.3, 114 ±5.1, 115 ±5.3 beats·minute^{-1}). The mean difference between the groups was 37 beats·minute^{-1} (99% CI 19-56 beats·minute^{-1}). The higher HR_{ex} in the CP group was a consistent finding for all but one of the CP-CON pairs (Figure 6.5). There were no significant between-pair differences in sweating rate (CP = 181.7 ±14.1 g·m^{-2}·h^{-1}, CON = 187.2 ±22.9 g·m^{-2}·h^{-1}). Figure 6.6 shows that individual CP-CON pair differences in sweating rates were, however, variable. There were no significant differences in RPE between the CP and CON subjects (for the end of minute 3 and 10 of bouts 1, 2, 3 respectively, CP = 11.3 ±0.88, 12.6 ±0.76, 12.5 ±0.90, 13.0 ±0.93, 12.6 ±0.92, 12.8 ±0.92. CON = 10.4 ±0.90, 10.4 ±0.79, 10.8 ±0.80, 11.2 ±0.90, 10.9 ±0.80, 11.2 ±0.90).

6.5 Discussion

This is the first reported study to investigate thermal strain in children and adolescents with spastic CP during treadmill walking in the heat. As expected, during short duration walking exercise at the same speed and slope in a warm, moderately humid climate, the children and adolescents with mild, spastic CP, compared with their individually matched (age, body size, biological maturity, gender, race) healthy CON demonstrated: i) higher metabolic rates, ii) greater ΔT_{re}, iii) greater ΔT_{sk}, iv) higher HR_{ex}, and v) similar sweating rates. Contrary to our hypothesis, there were no differences in RPE between the CP and CON subjects.

For practical reasons, mechanical work or power was not measured in this study. Although the methods (kinematic-based estimates of mechanical power) have theoretical limitations (28), inter-subject differences in mechanical power have been shown to explain 87% of the inter-subject differences in $\dot{V}O_2$ for subjects with CP walking on the treadmill (0.83 m·s^{-1}) (26). This would suggest that much of the increased metabolic rate seen in subjects with CP during

treadmill walking maybe due to their working harder than CON. Other research (27) has also shown that that the low walking economy in those with CP is related to increased lower limb antagonist muscle co-activation. Independent of why those with CP have a lower walking economy, when they are working at a higher absolute metabolic rate than CON subjects are, they need to dissipate a greater absolute heat load. In this present study, the greater ΔT_{re} and ΔT_{sk} in the CP group relative to CON are indirect indicators of the increased heat gain in the CP group. The CP group is unable to completely dissipate the metabolic heat load they produce while treadmill walking at a moderate intensity in the heat. Previous research with subjects with mild CP showed that those with CP required 60% more metabolic energy as a group than healthy CON walking on the treadmill at the same speed ($0.83 m \cdot s^{-1}$) (27). In our study those with CP had a 40% higher $\dot{V}O_2$ on average than did the CON. Since little information is available on the gross motor function of this previous group of subjects, it is difficult to determine why they were less economical relative to CON than the present group of subjects with CP. The comfortable ground walking speed of the previous group ($1.3 m\ s^{-1}$) reported elsewhere (12), was similar to that reported for the present subjects (Table 6.2).

Since HR is linearly related to $\dot{V}O_2$ at submaximal exercise intensities (1), the increased HR_{ex} in the CP group reflects their higher $\dot{V}O_2$ compared with the CON group. The higher HR_{ex} in the CP group may also reflect their increased thermal strain compared with CON. Since there were no differences in sweating rates between the CP-CON pairs, the subjects with CP may have been relying more on dry heat loss (conduction and convection) than their able-bodied counterparts; i.e., the increased HR_{ex} in those with CP may therefore have been due (in part) to an attempt to maintain cardiac output when an increased proportion of the blood was diverted to the skin for thermoregulation. It has been suggested that skin blood flow is determined more by core temperature than by sweating (30) and in this study the subjects with CP had the higher ΔT_{re} and

peak T_{re}. Further research is needed to determine if the skin blood flow of those with CP differs from that of CON during moderate intensity treadmill walking exercise in the heat. Our findings also support the hypothesis of Falk et al. (8), who suggest that the higher T_{re}, T_{sk}, and HR values of the younger compared with older able-bodied boys during treadmill walking (29), but not during cycling (9) may be due to age-related differences in walking economy (10), i.e., younger boys are less economical than older boys and thus produce more metabolic heat.

Although this study, which used a repeated measures design (where each subject with CP was compared to their CON match) was not designed to investigate inter-subject (CP group) differences in thermoregulatory responses to treadmill exercise in the heat, such differences among the subjects with CP may also exist. Figure 6.5 shows that by the end of the third exercise bout, six of the CP subjects had exceeded the target HR_{ex} range of 140-150 beats minute^{-1}. Further research with a larger group of subjects with CP, grouped perhaps by severity of CP, would help to clarify the findings in Figure 6.5.

Although changes (due to climatic and metabolic heat stress) in T_{re} lag behind changes in esophageal and tympanic temperature (20), Figure 6.2 shows that, especially in the CP group, the increases in T_{re} are occurring during the exercise bouts. That this relationship is less obvious in the CON group is likely due to their lower metabolic rate, since in a previous study (14) using short duration exercise in climatic conditions as in the present study, where metabolic rate was about 16% lower than in the present study, T_{re} did not change significantly from baseline throughout the chamber session for either the CP or the CON groups. With lower metabolic rates, T_{re} may respond too slowly to show increases in core temperature related to short duration exercise. However, for ethical and comfort reasons, measurement of body core temperature at the esophagus, the preferred method (23), was not feasible. We also chose not to measure tympanic temperature since it is related to both skin and environmental

temperature (19) and would have been at least somewhat influenced by the warm environmental conditions in this study.

As expected, the CP and CON subjects showed similar sweating rates. This finding is consistent with our previous work with this population with short duration, lower intensity arm cranking exercise in the heat (14).

Previous research has shown that for cycling exercise at a given power output, children and adolescents with CP perceive themselves to be working harder than healthy CON (3). When RPE was expressed relative to % of peak power, however, these inter-group differences disappeared (3). Bar-Or and Reed (3) suggest that the inter-group differences in RPE at the same intensity are related to the lower fitness levels in the CP subjects compared with CON. While we found the same pattern for RPE as in the previous study, these differences were not significant. *Post-hoc* power calculations suggest that with 10 subjects in each group, we had adequate power (.80) to detect differences in RPE of at least 2.9 units. The mean difference between the CP and CON groups in this study was 1.7 units. Thus the subjects with CP may have perceived themselves as working harder although the results are inconclusive. Since the previous authors (3) did not report on the severity of the CP of their subjects, and the testing modalities are different (cycling in the previous study, treadmill walking in the present study), it is difficult to determine the reason for the difference in the findings between the two studies. It is of clinical relevance, however, that these subjects with CP whose metabolic rates were on average 40% higher than in CON do not strongly perceive themselves as working harder. From a clinical perspective, those with mild CP may not be aware of their work rate. Further research is needed to determine in free living situations in the heat, if these children and adolescents with CP self-regulate their physical activity levels.

While neither group reached a T_{re} that is harmful to health, the pattern of those with CP (Figure 6.2) shows that they were continuing to gain heat (since skin temperature was stable through most of the chamber session, see

Figure 6.4) as the chamber session went on. By midway through the 2nd exercise bout, their ΔT_{re} was significantly higher than during the pre-exercise phase. Thus, had they continued to exercise they would likely have continued to gain heat. This is in contrast to the pattern seen in Figure 6.2 for the healthy children and adolescents. For most of the chamber session they were in thermal balance, neither gaining, nor losing heat. It was only by the end of the third exercise bout that their ΔT_{re} increased. From a clinical standpoint, if children and adolescents with CP who are engaging in short duration exercise at moderate intensities in the heat do not self-regulate their activities, or are in situations where they are with able-bodied children (such as a school sports team) and thus are not able to self-regulate, they may be at risk for discomfort, which could affect enjoyment of the activity and possibly athletic performance.

It is unlikely that any inter-group differences in thermal strain were masked by differences between the groups in anthropometric variables or biological maturity. We successfully matched these characteristics (Table 6.1). In addition, although we did not *a priori* match for the sum of 4 skinfolds or body surface area, these characteristics were also not significantly different between the groups (Table 6.1). Moreover, during visit 2, the subjects were similarly hydrated (loss of body fluid over the time in the chamber was 0.04 ±0.05 % and 0.01 0.10 % body mass, for the CP and CON groups, respectively) and acclimated to the testing environmental conditions (see Methods, above).

In conclusion, those with CP, compared with individually matched CON, demonstrated a higher $\dot{V}O_2$ during short duration treadmill walking in the heat. Consistent with a higher metabolic heat load they also demonstrated greater increases in body temperatures and HR. Since sweating rates were not different between the CP and CON groups, further research is needed to determine if those with CP rely more on dry heat loss. Finally, the failure to find a clear inter-group difference in RPE and the pattern of increasing rectal and skin temperature gain over time within the CP group suggest that further research is also required

to determine if these subjects with mild, spastic CP self-regulate their physical activity during free living under climatic conditions as in this study.

6.6 Acknowledgements

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Table 6.1. Subject characteristics. Mean (minimum-maximum) listed for characteristics 1-5. Frequencies listed for characteristics 6-8.

Variable		CP	CON
1.	Age, yr	13.0 (10.3-16.3)	13.0 (10.6-16.6)
2.	Body mass, kg	38.5 (31.5-70.2)	39.1 (30.8-62.9)
3.	Sum of 4 skin-folds, mm	37.1 (25.8-64.8)	35.6 (21.2-47.8)
4.	Arm span, cm	153.7 (141-173)	155.4 (147-170)
5.	Body surface area, m^2	1.35 (1.13-1.84)	1.35 (1.15-1.73)
6.	Pubertal stage	Tanner 1, n = 2	Tanner 1, n = 2
		Tanner 2, n = 4	Tanner 2, n = 5
		Tanner 3, n = 2	Tanner 3, n = 2
		Tanner 4, n = 2	Tanner 4, n = 1
7.	Gender	Boys, n = 7	Boys, n = 7
		Girls, n = 3	Girls, n = 3
8.	Race	Caucasian, n = 8	Caucasian, n = 8
		Black, n = 2	Black, n = 2

Although subjects were not *a priori* matched for the sum of 4 skinfolds and body surface area, there were no significant differences between the groups for these measures. CP = cerebral palsy; CON = control.

Table 6.2. Descriptors of cerebral palsy (CP) and gross motor function characteristics.

CP Subject	Topographic Distribution of Spasticity	Lower limb spasticity (MAS)		Severity (GMFCS)	GMFM%	CGWSm·s^{-1}
				II	83.3	1.1
1	Diplegia	*#R=1^{+}	*#L=1			
2	R hemiplegia	*R=1^{+}	L=0	II	93.1	1.6
3	Diplegia	R=2	L=2	II	55.5	1.2
4	L hemiplegia	R=0	L=1	I	95.8	1.5
5	Diplegia	R=1	*L=1^{+}	I	95.8	1.2
6	R hemiplegia	*R=1^{+}	L=0	I	97.2	1.2
7	Diplegia	*#R=1^{+}	*#L=1	II	59.7	1.2
8	Diplegia	*#R=1	*#L=1^{+}	II	62.5	1.0
9	Diplegia	*#R=1^{+}	*#L=1	I	84.7	1.1
10	Diplegia	*#R=1^{+}	*#L=1	I	91.7	1.3
Mean					89.1	1.2
SD					16.4	0.02

All the control (CON) subjects scored 100% on the GMFM, Dimension E. CGWS for the CON group varied from 1.1-1.5 m·s^{-1}.

* hamstrings muscle group = 2; #gastrocnemius muscle = 2. MAS = Modified Ashworth Scale. GMFCS = Gross Motor Function Classification System. GMFM = Gross motor function measure score for Dimension E (Walking, Running, and Jumping). CGWS = Comfortable ground walking speed. R = Right. L = Left

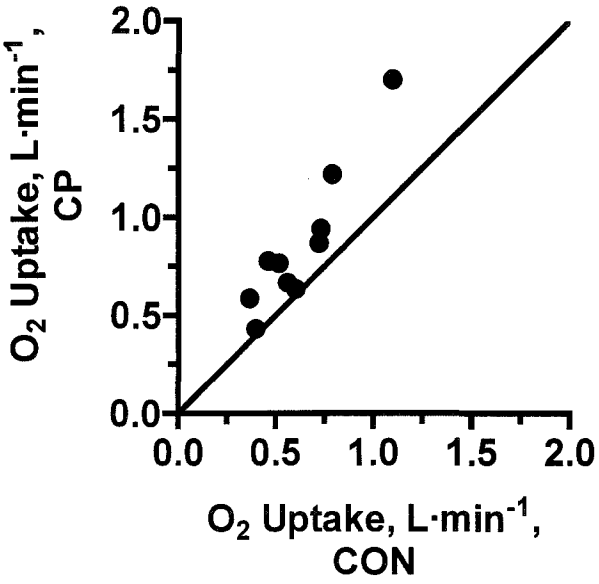

Figure 6.1. Oxygen uptake ($\dot{V}O_2$) during bout 3 for individual cerebral palsy (CP)-control (CON) pairs. The solid line denotes identity. As stated in the text, $\dot{V}O_2$ was significantly higher in the CP group, independent of bout (P = .0006).

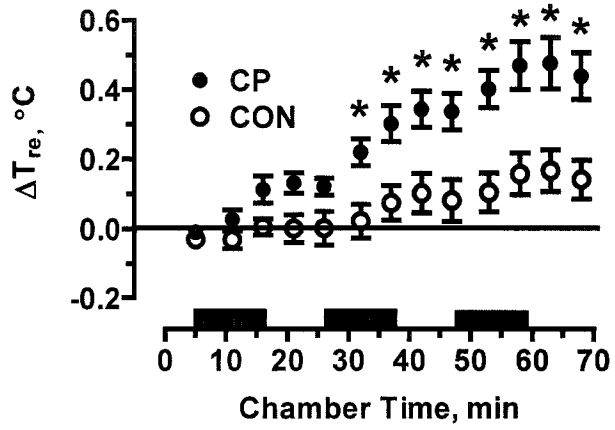

Figure 6.2. Change in rectal temperature (ΔT_{re}) during time in the chamber. Solid line indicates T_{re} prior to entering chamber. Group means and SEM shown. Filled boxes denote exercise periods. One-minute rest period after minute 3 (see text for details) not shown. *Cerebral palsy (CP) group significantly ($P<0.0002$) higher ΔT_{re} than control (CON) group at that specific time point.

(Not shown) The subjects with CP started to significantly ($P<0.0008$) gain heat from 32 minutes (6^{th} time point) in the chamber onwards. This did not occur in the CON subjects until minute 58 (11^{th} time point).

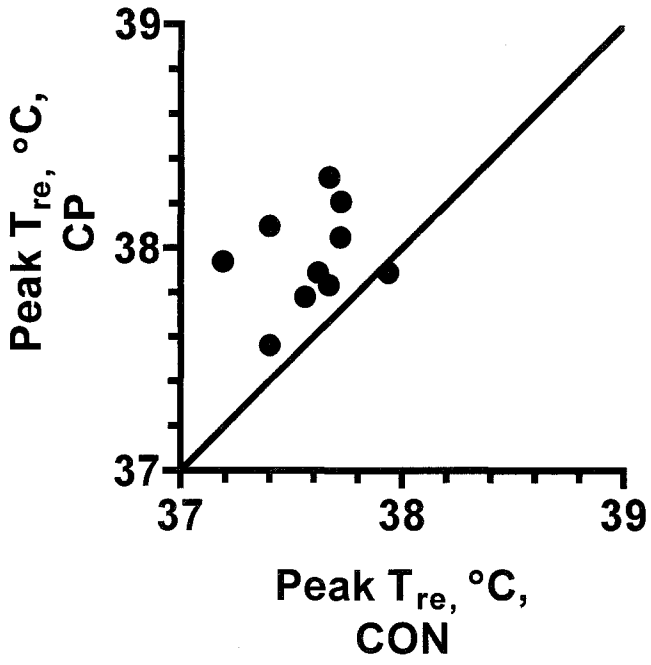

Figure 6.3. Peak rectal temperature (T_{re}) during time in the chamber. The solid line denotes identity. As stated in the text, peak T_{re} was significantly higher (P = .002) in the cerebral palsy (CP) group.

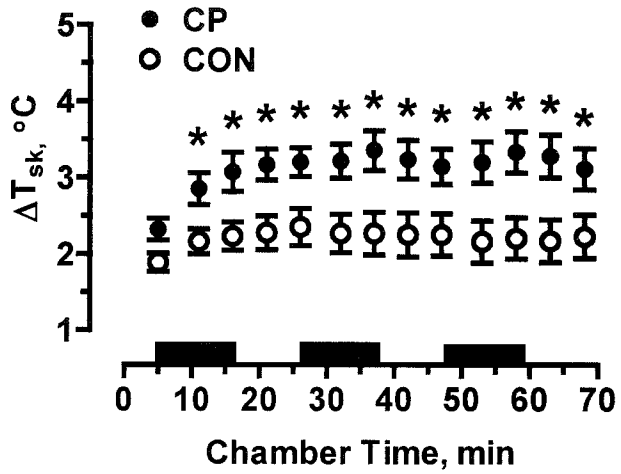

Figure 6.4. Change in skin temperature (ΔT_{sk}) during time in the chamber. Group means and SEM shown. Filled boxes denote exercise periods. One-minute rest period after minute 3 (see text for details) not shown.

*Cerebral palsy (CP) group significantly ($P<0.0002$) higher ΔT_{sk} than control (CON) group at that specific time point and significantly higher ($P<0.001$) ΔT_{sk} than upon entering the chamber.

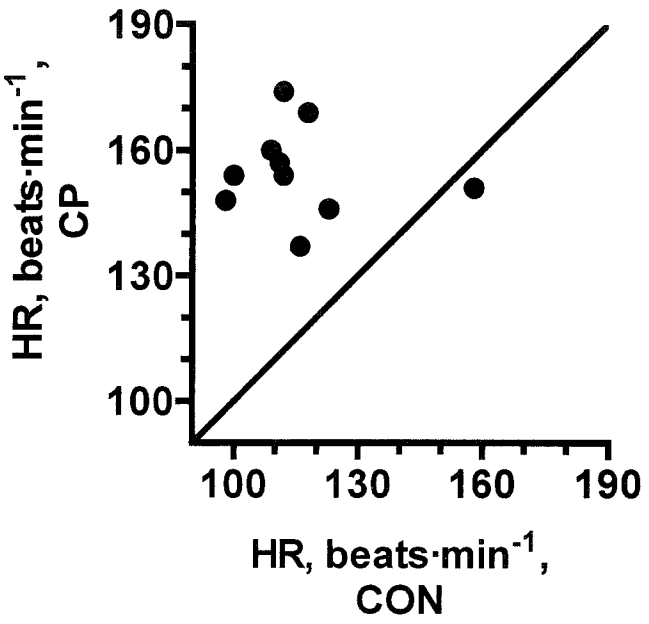

Figure 6. 5. Heart rate (HR) during the final minute of bout 3 for individual cerebral palsy (CP)-control (CON) pairs. The solid line denotes identity. The pattern was similar for bouts 1 and 2. As stated in the text, the final minute HR, independent of bout, was significantly higher in the CP group (P = .0001)

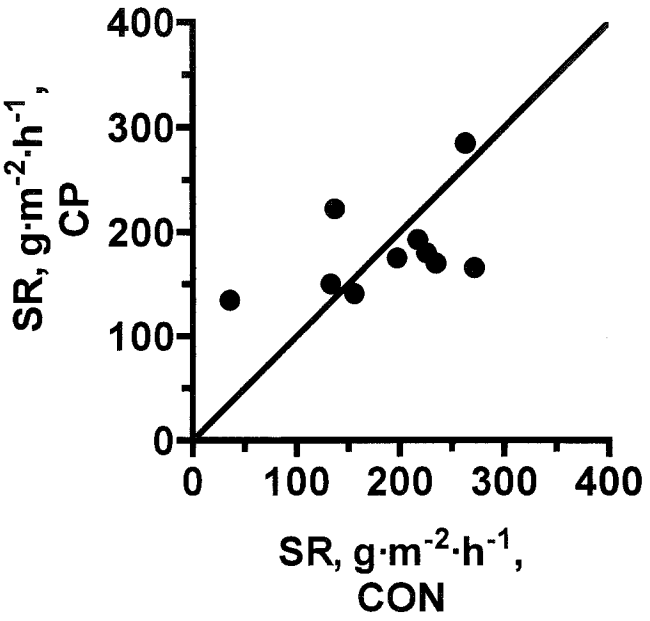

Figure 6.6. Sweating rate (SR) for individual cerebral palsy (CP)-control (CON) pairs. The solid line denotes identity. As stated in the text, there was no significant inter-group difference.

Chapter 7: Physical Activity Level is Associated with the O_2 Cost of Walking in Cerebral Palsy

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7.1 Abstract

Purpose: To determine, in children and adolescents with cerebral palsy (CP), the relationship between physical activity level (PAL), and i) oxygen cost of walking, and ii) peak $\dot{V}O_2$. **Methods**: In 11 subjects (10.6-16.3 yr) with mild CP, PAL, the ratio of total energy expenditure to resting energy expenditure, was determined from 3 days of heart rate (HR) monitoring (field), with individual HR-$\dot{V}O_2$ calibrations done in the lab. The oxygen cost of walking was measured during 3, 3-minute walks on a treadmill at 60, 75, and 90% of each subject's fastest treadmill walking speed (FWS). Subjects also performed a maximal treadmill exercise test. Alpha was set at .05. **Results**: One subject was an outlier and eliminated from all simple linear regression analyses. For the remaining 10 subjects, PAL (1.37 ± .18) was related (r = -.70 to -.84) to net $\dot{V}O_2$ at 60 and 75% FWS (13.1 ± 4.1, 16.2 ± 4.2 ml kg^{-1} $minute^{-1}$), net $\dot{V}O_2$ m^{-1}, averaged across the three speeds (.32 ± .23 ml kg^{-1} m^{-}) and % peak $\dot{V}O_2$ at all three speeds (54.5 ± 21.5, 63.5 ± 20.9, 75.5 ± 15.1%). PAL was not significantly related to net $\dot{V}O_2$ at 90% FWS (20.8 ± 5.3 ml kg^{-1} $minute^{-1}$), nor to peak $\dot{V}O_2$ (34.0 ± 9.2 ml kg^{-1} $minute^{-1}$). **Conclusion**: For this population, those with low PAL may also have a high oxygen cost of walking. These individuals' PAL are not related to their peak $\dot{V}O_2$. Further research is required to determine whether

interventions that decrease the oxygen cost of walking also affect PAL and whether changes in PAL affect the oxygen cost of walking.

7.2 Introduction

The term cerebral palsy (CP) denotes a "group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising early in development" (16). It occurs 2 to 2.5 times per 1000 live births (24). Of the subtypes, spastic diplegia and hemiplegia are the most common (24). One manifestation of the motor impairment is low walking economy. The oxygen uptake ($\dot{V}O_2$) during walking of those with CP can be up to three times higher than controls (CON) (3,27). High antagonist muscle co-activation in the lower limbs (27) and high mechanical power (26) are associated with the high oxygen cost of walking in this population. Use of ankle foot orthoses (11) and orthopedic surgery (4) improve walking economy. Children with CP are also less physically active than their peers. Compared to CON, a group of 10 subjects with CP, 9 of whom were ambulatory, demonstrated a 15% lower physical activity level (PAL) (29). Physical training that is mostly aerobic in nature (four times weekly over 9 months) may improve PAL in children with CP (trend for difference, P=.07) (28).

It has been suggested (1) that the low walking economy of children and adolescents with CP might be one cause of their early fatigability (4). Those with low walking economy would be walking at a higher relative exercise intensity or % peak $\dot{V}O_2$ (%$\dot{V}O_{2PEAK}$) compared to more economical individuals, and thus they would have less "metabolic reserve", and would therefore fatigue sooner. Although this hypothesis has yet to be explicitly tested in children and adolescents with CP, in healthy, running-trained boys who were assessed over a 2-5 yr period, $\dot{V}O_{2PEAK}$ (per kg body mass) did not change over time, whereas running economy and endurance performance both improved (5). Should low walking economy be associated with reduced endurance, the low PAL in boys

and girls with CP may be a compensatory mechanism to reduce or prevent fatigue.

It is unknown, however, whether PAL is associated with $\dot{V}O_2$ during walking in those with CP. The primary purpose of this study was to determine, for children and adolescents with mild spastic CP, whether there was a linear relationship between their PAL and oxygen cost of walking. Since these subjects also have reduced $\dot{V}O_{2PEAK}$ compared to their typically developing peers (8), a secondary purpose of this study was to determine if their PAL was linearly related to $\dot{V}O_{2PEAK}$. We hypothesized that low PAL would be associated with a high oxygen cost of walking and low $\dot{V}O_{2PEAK}$.

7.3 Methods

Subjects. Seven boys and four girls, 10.6-16.3 yr (body mass = 44.8 ±18.1 kg; arm span = 154.6 ± 10.2; sum of four skinfolds = 56.1 ± 39.2) with spastic diplegic (n=7) or hemiplegic (n=4) CP took part. Their biologic maturity was variable (Tanner 1 or 2, n=7, Tanner 5, n=3). All subjects could walk over ground without support and had mild CP, that is Level I or II based on the Gross Motor Function Classification System (18). Gross motor function and surgical history are described in Table 7.1. Eight subjects had walked on a treadmill within the previous year; one of them walked on a treadmill weekly. The subjects had not had orthopedic surgery within the previous year, nor had they taken medication to reduce spasticity within the 6 months prior to the study. Two of them habitually wore hinged ankle foot orthoses. The subjects had a similar degree of soft tissue contracture. The hip flexion contractures were no greater than 20°, while the hamstring contractures (knee extension limitation with the hip flexed to 90°) was on average 40°. Ankle dorsiflexion (knee extended) was at least neutral. The subjects were otherwise healthy. They had at least one parent or guardian with full-time employment and lived within a 15-minute drive of an urban center. All families had a vehicle. The subjects were not involved in

competitive sports during the time of this study. All of them reported to be physically active 1-2 h per week outside of school hours (games with neighborhood friends, walks with family members, horseback riding, exercising at a gym). They refrained from caffeine for 3 h, eating for 2 h, and heavy exercise for 8 h before coming to the lab for each visit. Written, informed consent was obtained from subjects at or over the age of 14 yr. For those under 14 yr, written, informed consent was obtained from a parent preceded by their own assent. The McMaster University Research Ethics Board approved this study and subjects were recruited through local children's rehabilitation centers.

Design. Subjects were tested during the early part of the school year (late summer to mid autumn). They visited the lab on 2 occasions and were visited in their homes in the morning and evening of 2 weekdays and 1 weekend day. Those who wore ankle foot orthoses continued to do so during their time in the study. At the first lab visit they were habituated to walking on the treadmill without holding the handrails, their $\dot{V}O_{2PEAK}$ and fastest treadmill walking speed (FWS) were determined and measurements for the individual HR-$\dot{V}O_2$ calibrations were completed. At the second lab visit they walked on the treadmill 3 minutes at each of 60, 75 and 90% (.8 ± .32; 1.0 ± .39, 1.3 ± .47 m s^{-1}) of their previously determined FWS. The lab and home visits were completed within 11.9 ± 11.6 and 12.9 ± 6.2 d, respectively. Subjects were in the study for 27.6 ±19.6 d. Each lab and home visit lasted 2-2.5 h and 25 minutes, respectively. The order of testing was randomized where test order could affect results.

Measurements. *Lab visit 1:* Questionnaires about physical activity (modified from Bar-Or (2)), health status and diet (time, content, and amount of the last meal and snack), were completed by the subjects with a parent's help if needed. Pubertal stage (pubic hair for boys, breast development for girls) was self-determined, based on photographs (13) according to the criteria of Tanner (25). Total body length, body adiposity and limb dominance were determined as previously described (12). Body mass (Mott Electronic Scale, UMC1000,

accuracy ± 10 g; Ancaster Scale Co. Ltd., Brantford, ON Canada) was measured after subjects emptied their bladder. Subjects wore shorts, a T-shirt, socks and running shoes during testing. Clothing and equipment were also weighed (Accuba Scale, 1,200, accuracy ± 0.1 g). The same clothing and footwear were worn for both lab visits. Classification of the topographic distribution of spasticity was based on Minear (15). One person (DM) determined severity of CP using the Gross Motor Function Classification System (18), a five-level system, where Level I describes those with the mildest involvement. To screen for contractures, lower limb passive range of motion was assessed (goniometry) using standardized techniques modified from McDowell et al. (14).

To subsequently determine PAL, $\dot{V}O_2$ and HR were measured for 4 minutes in the lying, sitting and standing positions. Subjects sat quietly for 15 minutes before the measures were taken and for 5 minutes between each measurement. The subjects were connected to an open circuit system by a mouthpiece (Vmax29 SensorMedics Corp., Yorba Linda, CA, USA). $\dot{V}O_2$, carbon dioxide output, ventilation, and respiratory rate was recorded and displayed at 20-s intervals. Just prior to data collection, gas flow was calibrated with a 3 l syringe and the O_2 and CO_2 analyzers were calibrated using gases of known concentration. HR (Polar Vantage XL, Polar CIC, Port Washington, New York) was also monitored continuously by the Polar HR monitor and stored in the receiver as 5-s averages.

Walking ability was assessed with the Walking, Running, and Jumping component of the Gross Motor Function Measure (21) and by determining the comfortable and fast walking speed on level ground (30 m walk way) using the median of a triplicate measurement. Subjects were taught to walk on a recently calibrated treadmill (Woodway Desmo M Tread Erogometer, Woodway USA, Waukesha, Wisconsin) without holding on to the handrails and their FWS on the treadmill was determined (12). Two subjects, who like the other subjects walked over ground without support, stabilized themselves by supporting themselves

slightly and periodically during all treadmill walks with their fingers on the handrails (alternating hands). A maximum exercise test on the treadmill was done according to procedures suitable for children and adolescents with mild cerebral palsy (8).

Lab visit 2: Information regarding health status (update) and diet were collected and body mass was measured as described in visit 1. Subjects walked on the treadmill for 3 minutes at 60, 75 and 90% of their previously determined treadmill FWS while ventilatory expired gas and HR data were collected as in visit 1. Between the walks the subjects rested until HR was within 10% of its pre-exercise value or remained steady and was no longer decreasing.

Home visits 1-6. The subjects were visited in the morning (after they had risen, and dressed) and evening (before they undressed for bed) of each of the three monitored days. For those (subjects) involved in physical education classes or organized extra circular physical activities, one of the monitored days was a day when these event(s) took place. In the morning, the heart rate monitor was secured on the subject with an elastic strap and surgical tape (Micropore, 3M, St. Paul MN). Electrode creme was used to ensure signal conductivity throughout the day. The HR monitor receiver was worn in a felt pouch on a belt at the waist over the non-dominant hip, under the clothing. HR was monitored continuously and recorded and stored in the receiver as 1-minute averages. In the evening of each monitored day, the subjects were revisited for equipment removal and interviewed regarding their activities for the day. Subjects were also asked what they did before and after HR monitoring each day, when they were not sleeping. Heart rate was monitored for 11 h daily (from about 8 a.m. - 7 p.m. on weekdays and from about 9 a.m. to 8 p.m. on weekends). Subjects slept 8-10 h per night.

Calculations and Data Reduction. Peak oxygen uptake, peak HR and determination of a plateau in $\dot{V}O_2$ during the maximal exercise test were calculated as previously described (8).

The oxygen cost of treadmill walking at the three different treadmill belt speeds was defined in three ways: i) net $\dot{V}O_2$ in ml kg^{-1} $minute^{-1}$ (net $\dot{V}O_2$), ii) average net $\dot{V}O_2$ in ml kg^{-1} m^{-1} (average net $\dot{V}O_2$ m^{-1}) and iii) $\%\dot{V}O_{2PEAK}$. Net $\dot{V}O_2$ was calculated by subtracting the subject's resting $\dot{V}O_2$ in l $minute^{-1}$ (sitting) from the average of the three 20 s $\dot{V}O_2$ values comprising the last minute of each sub-maximal treadmill walk. Conversion to a mass relative value was achieved by dividing by the subject's total body mass, including clothing and equipment. $\dot{V}O_2$ while sitting (the resting value) was calculated by averaging the six most consecutively stable 20s values from the 4-minute collection period. Steady state during the walks was determined as previously described (12). Each subject's average net $\dot{V}O_2$ m^{-1} was calculated by dividing net $\dot{V}O_2$ by the treadmill belt speed (m $minute^{-1}$) for that walk and then averaging across the three speeds. The $\%\dot{V}O_{2PEAK}$ was the ratio of the oxygen cost of the walk ($\dot{V}O_2$, in ml kg^{-1} $minute^{-1}$) to that particular subject's $\dot{V}O_{2PEAK}$, represented as a percentage.

Total EE d^{-1} was determined from the minute-by-minute HR measured during the three monitored days using a modification of the FLEX HR method (23) suitable and valid for children with CP (30). Artifacts, defined as HR < 35 beats $minute^{-1}$ > peak HR (7) and any sudden change in HR of > 60 beats $minute^{-1}$ that lasts for only 1 minute (9), were removed and replaced with interpolated HR values calculated by averaging the values previous and subsequent to artifact(s). No more than 4 minutes of consecutive artifact data occurred for any subject. Subject data loss due to artifacts varied from .5-2.1%. For three of the total 33 monitored days, the first 8.5 h were monitored, for two of the 33 days, the first 9 h were monitored. Since the missing hours were always at the end of the day and the interviews showed that the subjects engaged in resting-low intensity physical activities during this time, EE based on resting $\dot{V}O_2$ was used for these hours of missing data. In addition, due to equipment malfunction one subject had HR data for one weekday and one weekend day (full 11 h for each day). As the interviews showed similar physical activities were

performed on both weekdays, this subject's total EE d^{-1} was based on the two monitored days.

It was assumed that EE during the 13 unmonitored hours of each monitored day was resting EE since the interviews showed that non-monitored waking hours were times of very low physical activity. Resting $\dot{V}O_2$ in l $minute^{-1}$ was the average of the six most consecutively stable 20-s values $\dot{V}O_2$ value from each of the lying, sitting and standing positions. We chose not to use a ventilated hood for the lying position because we wanted all resting values to be measured under the same conditions. HR was determined for each of the resting positions by averaging HR over the same period as for $\dot{V}O_2$. Four calibration points were used for each subject's HR-$\dot{V}O_2$ relationship during non-resting periods. These were the HR and $\dot{V}O_2$ while standing, and the average HR and $\dot{V}O_2$ (the last 40 s) from the first three sub-maximal stages of the maximal exercise test. For the group, FLEX HR (30) was 105 ± 7.7 beats $minute^{-1}$. Total EE d^{-1} was calculated using an energy equivalent of 20.50 kJ l^{-1}. PAL was defined as the ratio of total EE d^{-1} to resting EE d^{-1}. Resting EE was used rather than lying EE, as lying EE was not always the lowest of the three EE values. We did not have the facilities to measure sleeping metabolic rate. PAL is traditionally used to estimate the level of physical activity because the ratio corrects for inter-subject differences in total EE due to differences in resting EE or differences in body mass.

Statistical Analyses. Simple linear regression was used to assess the relationship between PAL and each of the oxygen cost of walking variables (net $\dot{V}O_2$ at 60, 75, and 90% FWS, average net $\dot{V}O_2$ m^{-1} and $\%\dot{V}O_{2PEAK}$ at 60, 75 and 90% FWS) and between PAL and $\dot{V}O_{2PEAK}$. Any data points identified during the analyses as outliers (17) were removed and the remaining data re-analyzed. The effect of walking speed (treadmill belt speed) on the oxygen cost of walking variables was assessed with a one-way, repeated measures ANOVA. Significant differences between relevant pairs were determined with Tukey's HSD *post-hoc*

test. Alpha was set at .05. All analyses were performed using Statistica for Windows (Version 5.5, StatSoft Inc, Tulsa, OK).

7.4 Results

The group mean $\dot{V}O_{2PEAK}$, HR and the respiratory exchange ratio values were 34.0 ± 9.2 ml kg^{-1} $minute^{-1}$, 189 ± 12 beats $minute^{-1}$, 1.05 ± .11, respectively. A plateau in $\dot{V}O_{2PEAK}$ was reached during the maximum exercise test in 6 of 11 subjects (55%). Steady state was achieved in 90.1% of the sub-maximal treadmill walks. One subject was an outlier for all simple linear regression analyses due to a high PAL (1.83 compared a mean PAL of 1.33 ± 0.11 for the other subjects) and was eliminated for the regression analyses results stated below.

There was a significant, negative linear relationship between PAL and i) $\dot{V}O_2$ at 60 and 75% FWS (Figure 7.1), ii) average net $\dot{V}O_2$ m^{-1} (r = .79, P = .007, group mean average net $\dot{V}O_2$ m^{-1} = .32 ± .23 ml kg^{-1} m^{-1}), and iii) $\%\dot{V}O_{2PEAK}$ at all three speeds (Table 7.2). PAL was not (significantly) related to net $\dot{V}O_2$ at 90% FWS (Figure 7.1), or $\dot{V}O_{2PEAK}$ (Table 7.2). Net $\dot{V}O_2$ at 60% FWS (13.1 ± 4.1 ml kg^{-1} $minute^{-1}$) was significantly lower than at 75 (16.2 ± 4.2 ml kg^{-1} $minute^{-1}$, P = .04) and 90% FWS (20.8 ± 5.3 ml kg^{-1} $minute^{-1}$, P = .0002). Net $\dot{V}O_2$ at 75% FWS was significantly lower than that at 90% FWS (P = .002). Walking speed did not affect the average net $\dot{V}O_2$ m^{-1} (mean at 60, 75, 90% FWS = .34 ± .29, .32 ± .22, .32 ± .18 ml kg^{-1} m^{-1}, respectively). The $\%\dot{V}O_{2PEAK}$ at 60% FWS (54.5 ± 21.5%) was significantly lower than at 75 (63.5 ± 20.9%, P = .005) and 90% FWS (75.5 ± 15.1%, P = .0001). The $\%\dot{V}O_{2PEAK}$ at 75% FWS, was also significantly lower than at 90% FWS (P = .0005).

7.5 Discussion

The main study findings were: i) the oxygen cost of walking of children and adolescents with mild CP, with the exception of their net $\dot{V}O_2$ at 90% FWS, explained a large proportion (49-71%) of the variance in their PAL, and ii) there was no significant relationship between their PAL and $\dot{V}O_{2PEAK}$.

Our hypothesis that low PAL would be associated with a high oxygen cost of walking was, for the most part, confirmed. With one exception, there was a strong, negative linear relationship between PAL and the oxygen cost of walking, whether this cost was considered over time, over a distance, or relative to each subject's $\dot{V}O_{2PEAK}$. Those who had a lower walking economy, and thus less metabolic reserve, demonstrated lower PAL. This finding indirectly supports the suggestion of Bar-Or (1) that the low walking economy of these subjects might be one cause of their early fatigability (4). Subjects with low walking economy may be less active to conserve energy or prevent fatigue. As noted in the introduction, in healthy boys, their improved walking economy was associated with improved endurance performance (5). A direct relationship between the oxygen cost of walking and PAL, however, can not be inferred from the present results. Studies determining: i) whether an intervention known to improve running economy, such as ankle foot orthoses (11), also improves PAL, and ii) whether an increase in PAL, as may occur with physical training (28), also results in increased walking economy, would help clarify the relevance of the present findings.

The lack of a significant correlation between PAL and net $\dot{V}O_2$ at 90% FWS may reflect the small amount of time these subjects spend walking at such a fast speed, since this variable considers the oxygen cost of walking over time. The low PAL in these subjects compared to that reported for typically developing children and adolescents (1.7-2.0) (10), would seem to support this hypothesis. Visual examination of the graphs in Figure 7.1 also suggests that as walking speed increases, the strength of the linear relationship between PAL and net $\dot{V}O_2$ tends to decrease. It is unlikely that the failure to find a significant

correlation between PAL and net $\dot{V}O_2$ at 90% FWS is due to low statistical power. With alpha set at .05 and beta set at .20 (statistical power = .80) there were a sufficient number of subjects to detect significant correlations (r) of about ± .70 or stronger, that is strong correlations where at least half the variance in PAL could be accounted for (17). Correlations much below .70 (positive or negative) are considered moderate at best, and may be considered suspect (17).

We have previously shown high between-day reliability ($R \geq .95$) in net $\dot{V}O_2$ for children and adolescents with mild CP during treadmill walking at 60, 75, and 90% FWS (12) following the treadmill walking habituation protocol used in the present study. Since the previous subjects, similar to the present subjects, had varying amounts of prior experience walking on a treadmill, it is unlikely that the oxygen cost (of walking) variables of the present subjects were affected by their treadmill walking experience before participating in the study. The mean values for net $\dot{V}O_2$ at 60, 75 and 90% FWS are slightly higher than our previously reported values for this population (11.3, 13.4, 18.6 ml kg^{-1} $minute^{-1}$, respectively, averaged across the walks at each of the three speed conditions) (12). This difference is likely because the subjects in the previous study were less physically involved than the present subjects. Their Gross Motor Function Measure Dimension E scores (88.9%) and comfortable and fast over ground walking speeds (1.2, 1.7 m s^{-1}, respectively) were slightly higher than those reported here (Table 7.1).

To determine the oxygen cost of walking over a distance we assumed a linear relationship between net $\dot{V}O_2$ (per kg body mass) and speed (m $minute^{-1}$), as is typically assumed in the literature for this population (3,6). Although (theoretically) normalizing to the m^2 is correct (20), with a small sample size and the inherent variability with such samples, *post-hoc* ANOVA analysis (not shown) revealed that neither method was superior to the other in scaling for differences due to speed.

The group mean PAL of 1.56 reported for children (8.0 ±1.4 yrs) with CP who were mostly ambulatory (9 of 10 subjects) (29) is higher than the 1.33 found for the 10 subjects in the present study (excluding the outlier with a PAL of 1.8). The difference in PAL between the studies could be due to the different methods used to determine total EE (doubly labeled water in the previous study compared to the FLEX HR method in the present study). HR monitoring for 3 days and use of the FLEX HR method as was done in the present study, however, has been shown to provide an estimation of total EE similar to that derived from the doubly labelled water technique (30). It is also possible that our PAL values were lower than those in the literature because of our method for calculating PAL. We defined PAL as the ratio of total EE to resting EE. Sleeping EE rather than resting EE, however, was used in the previous study. We did not have access to a specialized chamber to measure sleeping metabolic rate and we chose *a priori* to measure $\dot{V}O_2$ during lying, sitting and standing under the same conditions. As stated in the Methods, lying $\dot{V}O_2$ was not used to determine resting EE because it was not always the lower of the resting values for these subjects. Since any reduction in PAL was systematic, is unlikely that our method for calculating PAL affected the pattern of the results. The subjects in the present study were on average 5 yrs older (13 ±1.4 yrs) and had a mean PAL 14.2% lower of than those in the previous study. Differences in PAL between the studies could be due to age-related reductions in habitual PA as has been reported for healthy boys and girls (22). Within the present group of boys and girls with CP, however, there was no significant relationship between age and PAL, between age and any of the oxygen cost of walking variables, or between age and $\dot{V}O_{2PEAK}$.

Our hypothesis that low PAL would be associated with a low $\dot{V}O_{2PEAK}$ was not confirmed. Parker et al. (19) found no significant relationship between the Gross Motor Function Measure-Dimension E (Walking, Running, and Jumping) scores of those with CP and their $\dot{V}O_{2PEAK}$, as measured with arm ergometry. *Post-hoc* analysis of the present results showed a significant, positive linear

relationship between Dimension E scores and PAL (r = .82, P = .004, n=10, excluding the subject with a high PAL). Thus it appears that $\dot{V}O_{2PEAK}$ is related to factors other than those associated with gross motor function. Our $\dot{V}O_{2PEAK}$, peak HR and the peak respiratory exchange ratio values were similar to those previously reported for this population (32.7 ml kg^{-1} $minute^{-1}$, 189 beats $minute^{-1}$, 1.1, respectively) using the same testing protocol (8).

Due to the sample size, only linear relationships between PAL and the oxygen cost of walking variables and $\dot{V}O_{2PEAK}$ were tested since linear relationships are potentially more stable. Figure 7.1, however, suggests a plateau in PAL-net $\dot{V}O_2$ at 60% FWS may exist for subjects with a very high oxygen cost of walking. For these subjects, their PAL may no longer be related to their walking economy, perhaps due to their very low PAL. A similar pattern was found for the PAL-%$\dot{V}O_{2PEAK}$ relationships (not shown). These potential, non-linear relationships, however, are based on only one or two data points and thus could be unstable. Further research with larger sample sizes is needed if more complex relationships are to be explored. Figure 7.1 shows that our failure to test non-linear relationships did not likely obscure any relationship between PAL and net $\dot{V}O_2$ at 90% FWS. A similar, unrelated scatter of data points was found when PAL vs. $\dot{V}O_{2PEAK}$ was plotted (not shown).

As noted in the results, one subject had a much higher PAL than the others and was excluded from the simple linear regression analyses. It is unclear from the results why this subject's PAL was high. His oxygen cost of walking and $\dot{V}O_{2PEAK}$ variables were similar to those of the group. The subject also met the same inclusion criteria as the others. That this subject was an outlier suggests our findings may be true for most but not all of this population.

In conclusion, there was a strong, negative linear relationship between PAL and the oxygen cost of walking in children and adolescents with mild CP, whether this cost was considered over time, over a distance or relative to each subject's maximum aerobic power. PAL was not significantly related to $\dot{V}O_{2PEAK}$,

which suggests that $\dot{V}O_{2PEAK}$ *per se* does not have an independent role in these subjects' PAL. Further research in this population to determine whether interventions that improve the oxygen cost of walking also affect PAL and whether changes in PAL affect the oxygen cost of walking would clarify the relevance of the present findings.

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Table 7. 1: Gross motor function and surgical history of the subjects.

GMFM-E, %	CWS, m s^{-1}	FWS, m s^{-1}	Surgical History
83.0 (17.1)	1.1 (0.20)	1.5 (0.52)	selective dorsal rhizotomy n=1; hamstrings lengthening n=4 (bilateral); hip adductor lengthening n=1 (bilateral), n=1 (unilateral); tendo-achilles lengthening n=2 (bilateral), n=1 (unilateral)

GMFCS, Gross Motor Function Classification System; GMFM-E, Gross Motor Function Measure Dimension E (Walking, Running, and Jumping); CWS, comfortable walking speed (over ground); FWS, fast walking speed (over ground); Mean (SD) listed for group data.

Table 7.2. Correlations between physical activity level and peak oxygen uptake and between physical activity level and the oxygen cost of walking relative to peak oxygen uptake.

	$\dot{V}O_{2PEAK}$ ml kg^{-1} min^{-1}	$\%\dot{V}O_{2PEAK}$		
		60 FWS	**75 FWS**	**90 FWS**
PAL	.44	-.84*	-.80*	-.83*

$\dot{V}O_{2PEAK}$, peak oxygen uptake; 60 FWS, 60% fastest walking speed; 75 FWS, 75% fastest walking speed; 90 FWS, 90% fastest walking speed; PAL, physical activity level. *P < .05.

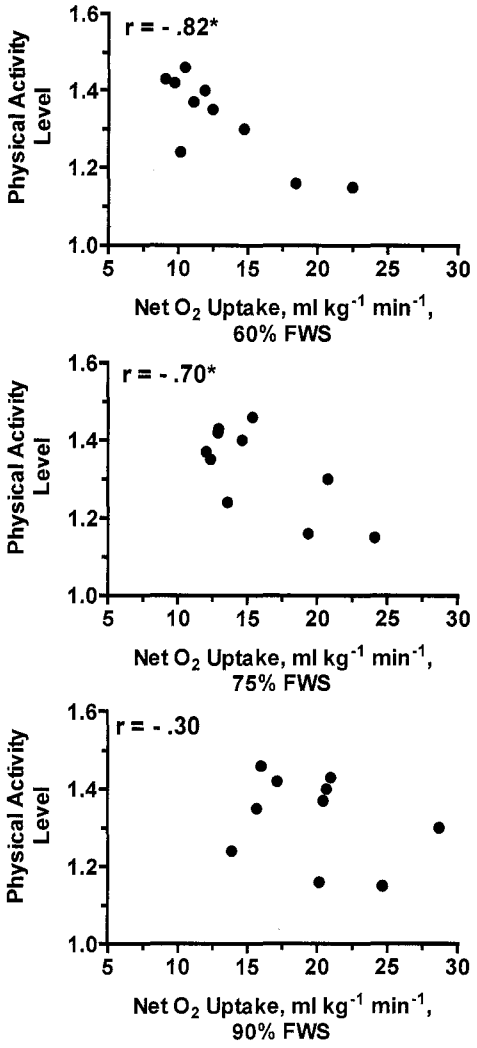

Figure 7.1. The relationship between physical activity level and net oxygen uptake at 60, 75, and 90% of the fastest walking speed. O_2, oxygen; FWS, fastest walking speed. *P < .05.

Chapter 8: Habitual Physical Activity Levels are Associated with Biomechanical Walking Economy in Children with Cerebral Palsy

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8.1 Abstract

Objective: To evaluate in children and adolescents with cerebral palsy: i) the relationship between habitual physical activity and biomechanical treadmill walking economy, and ii) whether treadmill belt speed or walking time affect economy. **Design**: Physical activity was measured in 11 subjects (10.6-16.3 yr) with mild cerebral palsy using a triaxial accelerometer. To determine biomechanical walking economy, subjects' stride lengths and vertical sacral excursions were measured during each minute of three, 3-minute walks on a treadmill (60, 75, and 90% of individually determined fastest treadmill walking speed). **Results**: Biomechanical walking economy at 60, 75 and 90% of (their) fastest speed each explained about half of the inter-subject variance in daily physical activity (movement counts). A similar relationship was found between these biomechanical walking economy variables and movement counts at or above the 80^{th} and 90^{th} percentile (total minutes d^{-1}, number of 5-minute bouts d^{-1}). Walking economy was 23.9% higher when subjects walked at 90 than when they walked at 60% of their fastest walking speed. No other speed-related effects on economy were found, nor did time affect economy. **Conclusions**: Within this population, those with high biomechanical treadmill walking economy

are the more habitually physically active. Treadmill belt speed, but not walking time, affects biomechanical walking economy.

8.2 Introduction

Cerebral palsy (CP) refers to a "group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising early in development" [1]. It occurs 2 to 2.5 times per 1000 live births and spastic diplegia and hemiplegia are the most common subtypes[2]. One manifestation of the motor impairment is low biomechanical walking economy (mechanical energy conservation). Mechanical energy expenditure (EE) of those with mild CP (able to walk without support) during treadmill walking at 3 km h^{-1} was found to be 50-70% higher than controls (CON), with the variation due to the method for calculation of mechanical power [3]. Children with CP also have low habitual physical activity (PA). Compared to CON, a group of 10 subjects with CP, 9 of whom were ambulatory, demonstrated a 15% lower physical activity level (PAL) [4]. The role of biomechanical walking economy in the level of habitual PA in CP, however, is unknown.

A meaningful investigation of the relationship between biomechanical walking economy and habitual PA requires that both variables be quantified appropriately. There is, however, no agreement in the literature on an optimal, global measure of biomechanical walking economy. Unnithan et al. [3] used a segmental dynamics approach to calculate total body mechanical EE during treadmill walking in the absence of kinetic data from a force plate. With this method, the kinetic and potential energy of body segments is estimated based on kinematic and anthropometric data, with or without various assumptions about energy transfer within and between body segments. Total body mechanical EE, calculated in this manner, however, can vary greatly depending on which assumptions are made [3].

In the mid 1990's Kerrigan et al. [5] introduced the biomechanical efficiency quotient (BEQ). The BEQ (which we consider a biomechanical economy quotient

since efficiency is not specifically assessed) is the ratio of the measured vertical sacral excursion during a gait stride to that predicted from sacral height and stride length data. Individuals who are healthy with a mature gait pattern would therefore have a BEQ of 1. The equation for the predicted value is based on a mathematical model the authors [6] developed from the kinematic gait data of able-bodied adults. The underlying assumptions are that the sacrum approximates the center of mass (COM) and that mechanical energy conservation is maximized when vertical COM excursion is minimized [7]. The BEQ, unlike the segmental dynamics model, avoids assumptions regarding the inertial characteristics of body segments and energy transfers. In adults and children with various neurological impairments, the BEQ is sensitive to changes in walking proficiency. The percent change in BEQ due to the use of ankle foot orthoses correlated ($r = .73$) with the percent change in comfortable walking speed [5]. Pilot data from our lab have shown the between-day reliability of the BEQ during treadmill walking to be high ($R > .90$) in both healthy adults, and children and adolescents with mild CP.

Habitual PA in CP has been objectively quantified by estimating total metabolic EE using the doubly labelled water technique [4] and the FLEX heart rate (HR) method [8]. To investigate the role of biomechanical walking economy in these individuals' habitual PA, a PA measure that is based on metabolic EE may not be appropriate, however, as metabolic EE is not simply related to kinematic events. Lower limb antagonist muscle co-activation, for example, is related metabolic EE in this population, at least during treadmill walking [9]. To investigate the role of biomechanical walking economy in habitual PA, a mechanical measure of PA, such as can be obtained from an accelerometer, may be more appropriate. Accelerometers are well accepted for use in PA studies with typically developing children [10] and have also been used to assess PA in young people with physical disabilities [11].

The primary purpose of this study was to determine the relationship between biomechanical walking economy, as measured by the BEQ, and the mechanical aspect of habitual PA, as measured by accelerometry. Since children and adolescents with mild CP are able to walk at different speeds both over ground and on a treadmill [9;12], we also chose to examine the effect of treadmill belt speed on the BEQ and minute-by-minute BEQ differences within a walk. We hypothesized that there would be a positive, linear relationship between habitual PA and biomechanical walking economy. We also hypothesized that the subjects' walking proficiency would be less at more demanding, faster speeds and thus biomechanical walking economy would be lower at faster, compared to slower speeds. Since 12-15 minutes of treadmill walking practice appears sufficient for habituation from a metabolic walking economy perspective [12], we hypothesized that there would be no minute-by-minute differences in the BEQ within a walk at any speed. It was assumed that the subjects in this study would be habituated to walking on a treadmill according to published procedures [12].

8.3 Methods

Subjects. Seven boys and four girls, 10.6-16.3 yr, with mild spastic CP, Level I or II as determined by from the Gross Motor Function Classification System [13], participated in the study (Table 8.1). Eight of the subjects had walked on a treadmill within the previous year. Five of them used the handrails; four did not. One subject regularly walked on a treadmill once per week (without holding on to the handrails). None of the subjects had orthopedic surgery within the previous year or had taken medication to reduce spasticity within the preceding 6 months. Two subjects habitually wore hinged ankle foot orthoses during the time they participated in this study. The subjects had a similar degree of soft tissue contracture. They had at least 105° of hip flexion and lacked no more than 20° of hip extension. With the hip extended, passive range of motion at the knee was full. With the hip at 90°, the subjects on average lacked about 40° of knee extension. Ankle dorsiflexion with the knee extended was at least 0° (neutral).

Subjects were otherwise healthy and on no medication that would affect the variables measured in the study. All subjects had at least one parent or guardian with full-time employment and lived within a 15-minute drive of an urban center. All families had a vehicle. No subject was a member of a competitive sports team during their time in the study. Eight of the subjects reported that they were physically active 1-2 h per week in unorganized PA (games with neighborhood friends, walks with family members). Three of them reported they were active on average for a similar amount of time per week in organized activities such as horseback riding or exercising at a gym. They refrained from caffeine for 3 h, eating for 2 h, and heavy exercise for 8 h before coming to the lab for each visit. Written, informed consent was obtained from subjects at or over the age of 14 yr. For subjects under 14 yr, written, informed consent was obtained from a parent, preceded by assent from the child. The study was approved by the McMaster University Research Ethics Board. Subjects were recruited through local children's rehabilitation centers.

Design. All subjects were tested during the early school year (late summer to mid autumn). The subjects visited the lab on 2 occasions and were visited in their homes in the morning and evening of three different days (2 weekdays and 1 weekend day). If they habitually wore ankle foot orthoses, then they continued to do so while in the study. During the first lab visit they were habituated to walking on the treadmill without holding on to the handrails and their fastest treadmill walking speed (FWS) was determined. During the second lab visit they walked on the treadmill 3 minutes at each of 60, 75, and 90% (.8 ± .32; 1.0 ± .40, 1.3 ± .48 m s^{-1}) of their previously determined FWS. The lab and home visits were completed within 16.4 ± 21.1 and 12.9 ± 6.2 d, respectively. Subjects were in the study for 27.6 ±19.6 d. Each lab and home visit lasted 2-2.5 h and 25 minutes, respectively. The order of testing was randomized where test order could affect results.

Measurements. *Lab visit 1:* The subjects completed questionnaires regarding habitual PA (modified from Bar-Or [14]), health status and diet (time, content, amount of the last meal and snack), with a parent's help if necessary. Pubertal stage (pubic hair for boys, breast development for girls) was self-determined, based on photographs [15] according to the criteria of Tanner [16]. Total body length, body adiposity and limb dominance were determined as previously described [12]. Body mass (Mott Electronic Scale, UMC1000, accuracy ± 10 g; Ancaster Scale Co. Ltd., Brantford, ON Canada) was measured after subjects emptied their bladder, while subjects wore shorts, socks and a T-shirt. To subsequently calculate total body mass and nude body mass (Table 8.1), all clothing, with the exception of underwear but including shoes and braces (if used) and equipment worn during the treadmill walks were also weighed (Accuba Scale, 1,200, accuracy ± 0.1 g). The same clothing and footwear were worn for both lab visits. Classification of the topographic distribution of spasticity was based on Minear [17]. One person (DM) determined severity of gross motor involvement using the Gross Motor Function Classification System [13], a five-level system, where Level I denotes those with the mildest involvement. To screen for contractures, lower limb passive range of motion was assessed (goniometry) using standardized techniques modified from McDowell et al. [18]. Gross motor function related to walking ability was measured using the Walking, Running, and Jumping component of the Gross Motor Function Measure [19]. Walking ability was also assessed by measuring the comfortable and fast walking speed on level ground (30 m walkway) using the median of a triplicate measurement. Subjects rested (sitting) between each trial until HR (Polar Vantage XL, Polar CIC, Port Washington, New York) was within 10% of its pre-exercise value. The subjects were taught how to walk on a recently calibrated treadmill (Woodway Desmo M Tread Erogometer, Woodway USA, Waukesha, Wisconsin) without holding on to the handrails and their FWS on the treadmill was determined[12]. Two subjects, who like the other subjects walked over ground without support, stabilized

themselves by supporting themselves slightly and periodically during all treadmill walks with their fingers on the handrails (alternating hands).

Lab visit 2: The subjects walked on the treadmill three times at each of 60, 75 and 90% FWS. They rested in between walks standing, supporting themselves with their arms, for 5-8 minutes until breathing was not labored and they indicated they were ready to begin the next walk. To calculate biomechanical walking economy, vertical sacral excursion and stride length during each gait cycle, during each treadmill walk, were measured using a rear mounted, previously calibrated, kinematic data acquisition system (OptoTrak, Northern Digital, Inc, Waterloo, Canada). Sampling rate was 50 Hz. The accuracy of measurement in our lab has been previously determined to be .2 mm. Four non-collinear infrared (IRED) markers were mounted on each of three lightweight thermoplastic shells. One shell was affixed at the sacrum on a wide elastic belt that the subjects wore, and one shell was affixed at the back of each shoe over the heel. These latter two shells were form fitting. All wires from the IREDS converged in a lightweight junction box that was affixed to the back of a snug-fitting vest that the subjects wore. A cable from the junction box connected it to a telemetric controller unit worn on the belt. A rechargeable battery that was also attached to the belt provided battery power to the IREDS.

Home visits 1-6: Each subject was visited in his or her home in the morning (after the subject had risen, and dressed) and evening (before the child undressed for bed) of three different days (2 weekdays and 1 weekend day). If the child took physical education at school, or was involved in organized PA, one of the PA monitoring days was a day when these event(s) took place (organized activities usually took place on the weekend). During the morning visit the PA monitoring equipment was secured on the subject. Activity was monitored with a triaxial accelerometer (RT3, Triaxial Research Tracker, Stayhealthy Inc., Eklander IA). All subjects were monitored with the same unit. The accelerometer in the RT3 is a single chip sensitive to acceleration in three orthogonal axis (X, Y,

Z, representing movement in the vertical, anteroposterior and mediolateral directions respectively when the monitor is worn as directed by the manufacturer). Acceleration is measured along each axis over user defined epochs (1 s or 1 minute). The data are stored as "activity counts". The relationship between acceleration (1 *g* =9.81 m s^{-1}) and activity counts, however, is unclear. The user can also set the device to record a vector magnitude (vector sum of the activity counts from the three axes) at each epoch. In this study the RT3 was set to measure vector magnitude activity counts and record them summed over each minute (activity counts = vector magnitude activity counts). The RT3 was worn in a felt pouch on a belt at the waist and secured with tape over the dominant hip, under the clothing. No swimming or bathing took place during the data collection periods so there was no need to remove or reapply the equipment during the day. Start time was noted on a watch synchronized to the internal clock in the accelerometer. In the evening of each monitored day, the subjects were again visited and the equipment was removed. The subjects were interviewed about what they did during the day. Whether and when the subjects climbed stairs or rode in a vehicle and for how long was also recorded. We also asked the subjects what they did before and after the monitoring each day, when they were not sleeping. The evening visit lasted about 25 minutes. In total PA was monitored for 11 h daily (from about 8 a.m. - 7 p.m. on weekdays and from about 9 a.m. to 8 p.m. on weekends). Subjects slept 8-10 h per night.

The RT3, a recently available triaxial accelerometer based on the technology of the previously available Tritrac R3D (Reining International, Ltd., Madison, WI), was used because it provides a reliable and clinically appropriate measure of habitual PA. The older, R3D has been shown to more accurately predict the $\dot{V}O_2$ of children during typical activities compared to the uniaxial WAM accelerometer [20]. When adults walk and run on a level treadmill, the newer RT3 predicts $\dot{V}O_2$ similarly to the R3D [21]. The RT3 is smaller (71 X 56 X 28 mm, 65.2 g) than the R3D (120 X 65 X 22 mm, 168 g), which may make it more

appropriate than its predecessor for quantifying PA in children. Pilot data from our lab with subjects with mild CP (n=11) whose PA was monitored simultaneously with the RT3 and HR over two weekdays and one weekend day, showed a high, positive correlation (r = .88) between the PAL, the ratio of total EE to resting EE [8] and the activity counts d^{-1} as measured by the RT3. Reliability (intraclass correlation) of the RT3 during mechanical vibration tests meant to simulate low and low-moderate PA levels is high (R = 0.99) indicating a strong relationship between axis across frequencies and across the monitors (n=23) [22]. Intra-monitor variability across frequencies and axis, also evaluated in this previous study showed a coefficient of variation (CV) of 0.9-15% with the CV decreasing as frequency increased. Similar findings with the RT3 were reported during treadmill walking and running [23].

Calculations and Data Reduction. *Kinematic Data*: Using custom software written by one of the authors (MRP), gait cycles were manually determined from the kinematic data from one IRED on the right foot. Motion data from the four IREDs were collected to give data redundancy in case of marker "drop out" due to obscuring of an IRED, such as by the contra-lateral limb during the swing phase of gait. Within a subject, the same IRED was used to determine all gait cycles. All cycles beyond 3 SD of the mean cycle length for a trial (0-1.3%) were considered atypical and were discarded. Stride length for all remaining gait cycles was calculated automatically by the software using initial contact (the lowest position of the heel during the gait cycle) as the start and end points of the stride. The sacrum, as an estimate of COM, was modeled by the lowest of the three IREDS that formed a downwardly pointed triangle on the sacral shell. Again the extra IRED and subsequent data redundancy at the sacrum were to ensure the motion of the sacrum was captured throughout each gait cycle. Vertical sacral height was the distance from the lowest of the sacral markers to the treadmill belt on which the subject was standing. Standing sacral height for each stride was estimated automatically by the software as the

average vertical height of the sacrum during the stride. In this manner inter-individual differences in the placement of the sacral shell relative to the actual sacrum were minimized. Measured vertical excursion of the sacrum during each stride was calculated by the software as the difference between the highest and lowest vertical sacral positions (relative to the treadmill belt) during the stride. Only strides for which all heel data points and all sacral data points were available were used in the calculation of the BEQ. The predicted vertical excursion of the sacrum for each gait cycle was determined from the following equation [5]: $p = ½ (h - \sqrt{(h^2 - (¼ l)^2)})$ where h was the sacral height and l was the stride length. The BEQ [5] was expressed as m/p where m was the measured vertical sacral excursion and p, the predicted value. A BEQ was calculated for each gait cycle. An average BEQ over minutes 1, 2 and 3 for each walk was also calculated.

Physical Activity Data: The sum of the minute-by-minute vector magnitude activity counts (11 h each day) was averaged over the three monitored days to yield an activity count d^{-1}. The total number of minutes (averaged across the three days) that the activity count was at or above the 80th and 90th percentiles for the group was also determined. From graphs of the minute-by-minute activity count data, the total number of blocks of 5, 10 and 20 minutes where the activity counts were at or above 90% of the 80th and 90th percentile cut points was determined to give the average number of blocks d^{-1} when activity was prolonged (5, 10, 20 minutes) at or above these percentiles. The 80th percentile was an activity count of 375, which for most subjects corresponded to walking at a slow or comfortable walk within a room, according to the interview information. The 90th percentile was an activity count of 736, which corresponded to faster walking, that occurred when subject reported to be walking with able-bodied friends or walking outside. For times when the subject reported to be in physical education class or taking part in other sporting activities, the activity counts were higher (over 1000).

Statistical Analyses. Simple linear regression was used to assess the relationship between each of the biomechanical walking economy variables (the BEQ at 60, 75 and 90% FWS) and each of the habitual PA variables (activity counts d^{-1}, number of minutes d^{-1} activity counts at or above the 80^{th} and 90^{th} percentile, number of 5-, 10-, 20-minute bouts d^{-1} activity counts at or above 80^{th} and 90^{th} percentile). The effect of treadmill belt speed (60, 75 and 90% FWS) and treadmill walking time (minute 1, minute 2, minute 3) was analyzed using a 2-way, repeated measures ANOVA. Tukey's HSD *post-hoc* test was used to identify relevant pairs that were significantly different. Alpha was set at .05. All analyses were performed using Statistica for Windows (Version 5.5, StatSoft Inc, Tulsa, OK).

8.4 Results

Some kinematic data loss occurred during the treadmill walks as the BEQ calculation program automatically rejected a cycle if there was any marker drop out. For 8 subjects, 98-100% of their typical strides for each treadmill walk went into the calculation of the BEQ variables. For the other three subjects, about half of their walks had minimal data loss (99-100% of their typical strides were used in the BEQ calculations). Of the remaining walks, all but one had at least 20 strides that went into the BEQ calculation. For one walk, for one subject, 7 strides were available with no marker drop out, with at least two strides used to calculate the BEQ for each minute of the three-minute walk. With respect to the accelerometer data (movement counts), there was no data loss due to mechanical failure of the accelerometer. Nine of the 11 subjects wore the accelerometer for all 11 h of each of the three monitored days. The other two subjects wore the accelerometer for the first 8.5 h of one of the weekdays and for the full 11 h of the other weekday and on the weekend day. Since the interviews from these latter two subjects showed that their activities (within subject) were similar during each of the weekday evenings monitored, the activity count data

from the same time on the other weekday for each subject was used to estimate their PA during the 2.5-h period when they did not wear the accelerometer.

Since the subjects' BEQ at 60, 75 and 90% FWS were highly inter-correlated (r >.98), the relationships between the BEQ at each speed, and a given PA variable were very similar (Figure 8.1, Table 8.2). The subjects' BEQ at 60, 75 or 90% FWS explained 54, 52, and 53%, respectively, of the variance in total activity counts d^{-1} (r = -.73, -.72, -.73, respectively, P = .01). Figure 8.1 shows that lower activity counts d^{-1} were associated with higher BEQ values (lower biomechanical walking economy). A similar relationship was found between the BEQ at each of the three speeds and the total number of minutes d^{-1} at or above the 80^{th} and 90^{th} percentile and the number of 5-minute bouts d^{-1} at or above the 80^{th} and 90^{th} percentile (Table 8.2). There was no significant relationship between the BEQ at any of the speeds and the number of 10- or 20-minute bouts d^{-1} at or above the 80^{th} and 90^{th} percentile (Table 8.2). Independent of time, the BEQ was lower when the subjects walked on the treadmill at 90% FWS than when they walked at 60% FWS (mean difference = 0.97 ± 0.7 95% CI, P = .03, Figure 8.2). There were no other inter-speed differences in the BEQ. The BEQ was not affected by time at any speed, nor was there any interaction between treadmill walking speed and time (Figure 8.2).

8.5 Discussion

The main findings from this study with children and adolescents with mild CP were as follows: i) biomechanical walking economy explained a large proportion (50%) of the variance in habitual PA, with the exception of prolonged PA (10- and 20-minute bouts), ii) biomechanical walking economy was higher (the BEQ lower) when the subjects walked at 90 than when they walked at 60% FWS, and iii) there were no minute-by-minute differences in biomechanical walking economy at 60, 75, or 90% FWS.

Our hypothesis that there would be a positive, liner relationship between habitual PA and biomechanical walking economy was, for the most part, confirmed. Subjects with low biomechanical walking economy or high BEQ values, showed low habitual PA, that is, low values for the number of activity counts d^{-1}, number of minutes d^{-1} activity counts were at or above the 80^{th} and 90^{th} percentile, and number of 5-minute bouts d^{-1} activity counts were at or above the 80^{th} and 90^{th} percentile. The lack of a significant correlation between the BEQ at any speed and more prolonged habitual PA, 10- and 20-minute bouts d^{-1} with activity counts at or above 80^{th} and 90^{th} percentile, likely reflects the similar low levels of prolonged activity in most subjects (Table 8.2), rather than a failure to find the correlations significant due to low statistical power. Low levels of prolonged moderate to high intensity PA are also typically seen in healthy children and adolescents of an age similar to those in the present study [24]. With the present sample size of 11, with alpha set at .05 and beta set at .20 (statistical power = .80), there was sufficient statistical power to detect positive or negative correlations of about .70 or stronger, that is, correlations where at least half the variance in habitual PA could be accounted for. Correlations (positive or negative) less than .70 are considered moderate at best, and may be considered suspect [25]. An examination of the curves suggested by the data in Figure 8.1, however, suggests there may be asymptotes at each end. If this were to be the case, then for subjects with very high and very low BEQ values there would no longer be a relationship between their BEQ and habitual PA. These potential non-linear relationships, however, are based on only one or two data points in the present study and thus could be unstable. Further research with larger sample sizes is needed if more complex relationships are to be explored.

It is difficult to determine from the movement count values reported in this study whether the subjects with CP had low levels of habitual PA compared to typically developing children and adolescents. The study was not designed to

answer this question or test such a hypothesis. In addition, there are no data in the literature for RT3 activity counts for those with CP or for typically developing children or adolescents. As noted in the Methods, however, PAL values (total EE/ resting EE) were calculated for the present subjects using HR, simultaneously measured along with activity counts and individual HR-$\dot{V}O_2$ calibrations (not reported) done in the lab. The mean HR-based PAL for the group was 1.37 ± .18. These values are lower than the 1.56 ± .18, calculated using doubly labeled water in mostly ambulatory (8 of 9 walked), but younger children (mean age 8 yrs) with spastic diplegic CP [4]. Physical activity levels (also calculated using doubly-labeled water) for typically developing children and adolescents by contrast, are higher (1.7-2.0) [26]. Between-study differences in the age of the subjects with CP and the methods for calculating PAL make direct comparisons between the studies difficult. The data, however, suggest that although the subjects in the present study have mild CP, their habitual level of habitual PA is likely compromised. These subjects' BEQ values on the other hand, are all > 1 indicating reduced biomechanical walking economy [5]. The BEQ values in the study varied between 1.5 and 11.2 which are within the range of values (1.8-26.7) previously reported for children and adults of varying ages with different types of neurological conditions, but who all walked independently [5]. Interestingly, two of the subjects in this previous study (ages 8 and 9 yrs) had CP. Their BEQ values at a comfortable walking speed over-ground were 1.9 and 17.3, respectively. The BEQ values in this present study appear to reflect values for subjects with a neurologic impairment, but whose biomechanical walking economy is not as severely reduced as some the subjects in the previous study. This probably reflects the milder nature of the neurologic impairment of the present subjects compared to those in the previous study. All subjects in the previous study, for example, wore ankle foot orthoses, while only two subjects did in the present study. Whether walking over ground compared to on a treadmill affects the BEQ is unknown.

Although we found a strong relationship between biomechanical walking economy and habitual PA, it remains unknown whether low biomechanical walking economy results in low habitual PA. Bar-Or [27] has suggested that low walking economy, might be one of the causes of these subjects' early fatigability [28]. If that is the case then these subjects may "self-regulate" their level of PA to avoid fatigue. Further research is needed to determine whether interventions used to improve walking proficiency in this population, also result in improved biomechanical walking economy, and if improved biomechanical walking economy corresponds to an improvement in habitual PA. It is also possible that higher levels of habitual PA result in improved biomechanical walking economy. Exercise programs, which presumably increase habitual PA (at least temporarily) have been shown to improve the metabolic economy of locomotion of typically developing children [29]. Research determining the effect on biomechanical walking economy of increasing habitual PA, perhaps through an exercise intervention program, would help to clarify whether low biomechanical walking economy might in part be the result of low habitual PA.

We hypothesized that biomechanical walking economy would be lower (and the BEQ higher) at faster, compared to slower speeds. This hypothesis was not confirmed. From the data it is not clear why biomechanical walking economy was higher at the fastest compared to the slowest speed. When subjects similar to the present group walked at 90% FWS, their $\dot{V}O_2$ stride^{-1} was (found to be) significantly higher than when they walked at 60% FWS [12]. This indicates that subjects with mild CP are more metabolically economical when walking at the slower rather than the faster speed. When individual subjects in the present study are considered, however, there is much variability in the effect of treadmill walking speed on the BEQ. Four of the subjects showed the hypothesized pattern; their BEQ was lower at 60 compared to 90% FWS. One subject showed no difference in BEQ at these two speeds. The remaining six subjects showed the group pattern, with their BEQ higher at 60 compared to 90% FWS. The effect

of speed on the BEQ, appears to be associated with the subject's biomechanical walking economy. Subject's mean BEQ averaged across the two speeds was highly and negatively correlated ($r = -.97$, $P=.0001$) with the difference in BEQ between 60 and 90% FWS (BEQ at 90% FWS - BEQ at 60% FWS). A more complete answer to the question of the effect of treadmill belt speed on BEQ is that the effect is highly related to the subject's BEQ. From the equation predicting this relationship ($y = -0.652x + 1.3571$) it appears that the transition BEQ value is just over 2 (2.08). Subjects with a mean BEQ above this value may be more economical at 90% FWS, subjects below this value, at 60% FWS.

Interestingly, *post-hoc* statistical analysis showed that the subjects' speeds at 90% FWS on the treadmill were not significantly different than their CWS over ground, whereas their speeds at 60% FWS on the treadmill were significantly slower ($.26 \pm .4$ m s^{-1}) than the CWS over ground. It appears that as a group, these subjects could not walk on the treadmill much faster than their comfortable over ground walking speed.

Since a 12-15-minute treadmill walking practice session appears sufficient for habituation from a metabolic walking economy perspective [12], we hypothesized that there would be no minute-by-minute differences in the BEQ within a walk at any speed. This hypothesis was confirmed. Our finding of no minute-by-minute differences in biomechanical walking economy agree with the finding of no minute-by-minute differences in metabolic walking economy, after steady state is reached at minute 2 of a 4-minute walk [9]. The subjects with CP in this previous study were similar to the present subjects and were habituated to walking on the treadmill in a manner similar to the procedures used in the present study [9].

One possible limitation of this study is the large variability in the ages of the subjects, since habitual PAL generally decreases with age in typically developing children and adolescents [24]. When the relationship between habitual activity (activity counts d^{-1}) and age was assessed *post-hoc*, however, these two

variables were not significantly correlated (r = .33, P=.32). Similarly, there was no significant relationship between the other habitual PA variables and age. Thus there is likely no bias in the habitual PA data due to age. Age was also not significantly related to the subjects' mean BEQ (r = .39, P = .23).

Another study limitation is that since the BEQ is a global measure of biomechanical walking economy, the particular aspect(s) of the subject's walking that contribute to their low biomechanical walking economy is unknown. In healthy adults, the major determinant than minimizes vertical sacral excursion appears to be heel rise. Heel rise from foot-flat raises the sacrum when it is at its minimum height and thereby reduces its vertical excursion by up to 66%, compared to what vertical sacral excursion would be with a theoretical compass gait [30]. Further research is required to assess whether heel rise has a similar role for subjects with CP or whether other factors are major determinants of minimization of vertical sacral excursion for this population.

In conclusion, children and adolescents with mild CP who are the more habitually physically active have a high biomechanical treadmill walking economy. Treadmill belt speed, but not walking time, also affects biomechanical walking economy. Further research is required to determine: i) activity counts from the RT3 accelerometer that reflect habitual PA in healthy children and adolescents, ii) differences in the BEQ of both typical subjects and those with mild CP during over ground compared to treadmill walking, iii) the effect on the BEQ and habitual PA of interventions designed to improve walking proficiency or habitual PA in this population, and iv) what aspect(s) of the walking pattern are the major determinants for minimization of vertical sacral excursion in those with CP.

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8.7 References

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Table 8. 1. Subject characteristics

Subjects	7 boys, 4 girls	**Topographic Distribution of Spasticity**	Diplegia, n=7 Hemiplegia, n=4
Age, yr	13.0 (2.2)	**GMFCS**	Level I, n=7, Level II, n=4
Body Mass, kg	44.8 (18.1)	**Lower limb dominance**	Left, n=6, Right, n=5
Sum of 4 skinfolds, mm	56.1 (39.2)	**GMFM-E, %**	83.0 (17.1)
Arm Span, cm	154.6 (10.2)	**CWS, m s^{-1}** **FWS,m s^{-1}**	1.1 (0.20) 1.5 (0.52)
Pubertal Status	Tanner 1 or 2, n=7 Tanner 5, n=3	**Surgical History**	SDR, n=1 HL, n=4 (BI) HAL, n=1 (BI) n=1 (UNI) TAL , n=2 (BI), n=1 (UNI)

GMFCS, Gross Motor Function Classification System; MAS, Modified Ashworth Scale; GMFM-E, Gross Motor Function Measure Dimension E (Walking, Running, and Jumping); CWS, comfortable walking speed (over ground); FWS, fast walking speed (over ground); SDR, selective dorsal rhizotomy; HL, hamstring lengthening; BI (bilateral); HAL, hip adductor lengthening; UNI, unilateral; TAL, tendo-achilles lengthening; Mean (SD) listed for group data.

Table 8. 2. Correlations for relationships between the biomechanical economy quotient and daily physical activity at or above the 80th and 90th percentile for the group. Group mean (SEM) for activity count data also shown.

	Activity Counts at or above 80th percentile				**Activity Counts at or above 90th percentile**			
	BEQ 60	**BEQ 75**	**BEQ 90**	**Mean (SD)**	**BEQ 60**	**BEQ 75**	**BEQ 90**	**Mean (SD)**
# minutes d^{-1}	-.73	-.73	-.75*	132.1 (14.0)	-.77	-.75	-.75*	66.0 (9.7)
# 5-minute bouts d^{-1}	-.69	-.69	-.72*	13.4 (2.3)	-.69	-.69	-.71*	4.8 (1.0)
#10-minute bouts d^{-1}	-.55	-.55	-.57	3.2 (0.8)	-.48	-.45	-.45	1.0 (0.3)
#20-minute bouts d^{-1}	-.43	-.43	-.42	0.9 (0.4)	-.40	-.36	-.37	0.2 (0.1)

BEQ, biomechanical economy quotient; 60, 60% of fastest treadmill walking speed; 75, 75% of fastest treadmill walking speed; 90, 90% of fastest treadmill walking speed; #, number; *P<.05.

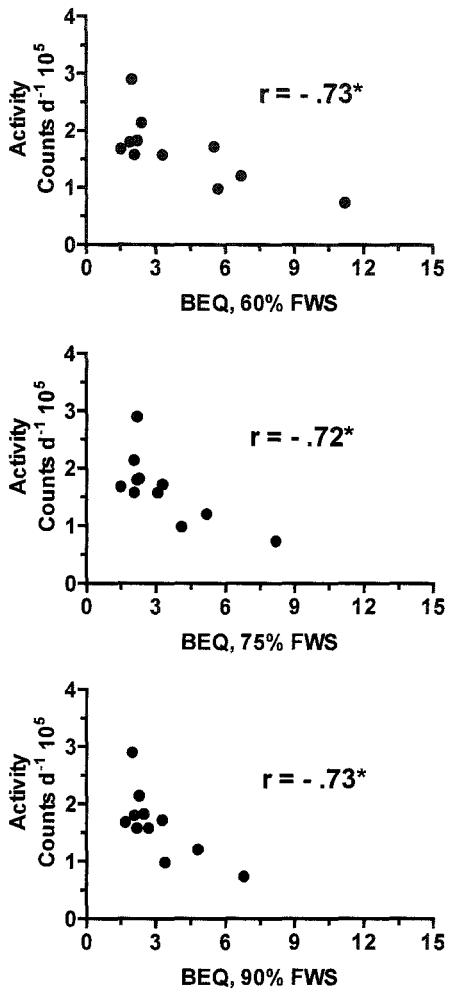

Figure 8.1. The relationship between activity counts d^{-1} and biomechanical walking economy at 60, 75, and 90% FWS. BEQ, biomechanical economy quotient. FWS, fastest walking speed. *P=.01.

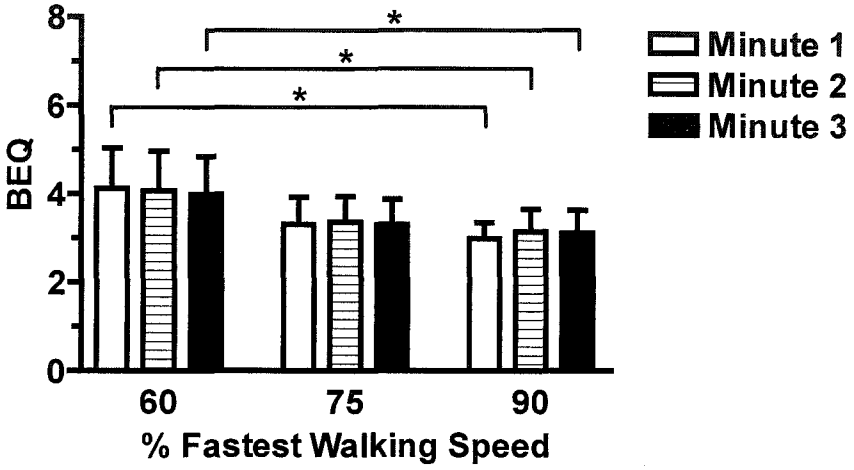

Figure 8.2. The effect of treadmill walking speed on biomechanical walking economy.

*90% fastest walking speed < 60% fastest walking speed (P <.05).

BEQ, biomechanical economy quotient. Group means (SEM).

CHAPTER 9: GENERAL DISCUSSION AND FUTURE RESEARCH DIRECTIONS

9.1 Overview and Main Findings

The O_2 cost of walking in children and adolescents with CP: i) is higher than in able-bodied controls (Campbell and Ball, 1978; Duffy et al., 1996; Johnston et al., 2004; Rose et al., 1990; Rose et al., 1993; Unnithan et al., 1996a), ii) is associated with high, lower limb antagonist muscle co-activation (Unnithan et al., 1996a) and poor mechanical energy conservation (high total body mechanical power) (Unnithan et al., 1999), and iii) can be reduced by certain interventions designed to improve walking proficiency (Dahlbäck and Norlin, 1985; Maltais et al., 2001; Massin and Allington, 1999; Park et al., 2001; Schwartz et al., 2004). Although it has been suggested (Bar-Or, 1983) that this high energy cost of walking may be one reason for the early fatigability reported in CP (Dahlbäck and Norlin, 1985), little is known about the implications of the high energy cost of walking in this population. Six studies (Chapters 3-8) were undertaken to answer questions about selected implications. Three studies (Chapter 3, 4, 8) answered questions related to habituation to treadmill walking, a protocol that allows for ease of data collection and control of walking speed. In Chapter 3, questions were answered from a metabolic and cardiorespiratory perspective, in Chapter 4, from an electromyographic (co-activation) perspective, and in Chapter 8, from a biomechanical walking economy perspective. Two studies, Chapters 5 and 6, addressed the implications of the O_2 cost of exercise to these subjects' thermoregulatory responses during exercise in the heat. The implications, to their level of habitual activity, of their high O_2 cost of walking and low biomechanical walking economy, were addressed in Chapters 7 and 8, respectively. The main findings from these studies are as follows:

1. Reliable net metabolic and cardiorespiratory variables may be obtained in subjects with mild spastic CP during treadmill walking following one 12-15-minute treadmill walking practice session (Chapter 3).
2. In subjects with mild spastic CP, 12-15 minutes of treadmill walking practice may be sufficient time to obtain stable lower limb antagonist muscle co-activation and stride length by minute 2 of a fast, 3-minute treadmill walk (Chapter 4).
3. Following 12- 15 minutes of treadmill walking practice, independent of walking time, lower limb antagonist muscle co-activation at the thigh in subjects with mild spastic CP is higher on the non-dominant side (Chapter 4).
4. For subjects with mild spastic CP who are habituated to walking on the treadmill, treadmill belt speed, but not walking time, affects biomechanical walking economy (Chapter 8). The effect of treadmill belt speed on biomechanical walking economy may be related to the subject's average biomechanical walking economy (Chapter 8).
5. Subjects with spastic CP demonstrate thermal strain responses similar to able-bodied CON during short duration, lower intensity upper body exercise in the heat when metabolic heat production is similar (Chapter 5).
6. When subjects with mild spastic CP walk on the treadmill in the heat, they require more metabolic energy (and thus produce more metabolic heat) and demonstrate greater thermal strain than able-bodied CON (Chapter 6).
7. Low PAL in subjects with mild spastic CP is associated with a high O_2 cost of walking but there is no relationship between PAL and $\dot{V}O_{2PEAK}$ (Chapter 7).
8. For subjects with mild spastic CP, those with high biomechanical walking economy are the more habitually physically active, when PA is assessed mechanically by accelerometry (Chapter 8).

9.2 Treadmill Walking

9.2.1 Habituation to Treadmill Walking

It was shown that 12-15 minutes of treadmill walking practice time may be sufficient for habituation to treadmill walking if one wishes to measure physiologic responses such as $\dot{V}O_2$ (Chapter 3), lower limb antagonist muscle co-activation (Chapter 4) or biomechanical variables such as stride length (Chapter 4) or biomechanical walking economy (Chapter 8).

Walking practice sessions of 15-20 minutes prior to collection of metabolic, cardiorespiratory, co-activation, and biomechanical variables have been reported in the literature (Jeng et al., 1996; Maltais et al., 2001; Unnithan et al., 1999; Unnithan et al., 1996a) for children and adolescents with CP. In other cases with this population, the researchers have not stated if or how much walking practice preceded testing (Dahlbäck and Norlin, 1985; Rose et al., 1989). A 5-minute practice session has also been used. Following 5 minutes of treadmill walking practice, Keefer et al. (2002) found no significant between-trial (within-day) differences in net $\dot{V}O_2$ (trials 1 and 2 = 6.6 ml kg^{-1} $minute^{-1}$, trial 3 = 6.2 ml kg^{-1} $minute^{-1}$, $P < 0.05$) for 6-15 year olds with spastic hemiplegic CP walking on the treadmill at 0.67 m s^{-1}. The effect on biomechanical and EMG variables of a 5-minute treadmill practice session is unknown. Based on the data presented in Chapter 4, however, a walking practice session of 5 minutes may not be sufficient if co-activation is to be measured, at least at a fast walking speed. In this study we found that even after a 15-minute practice session, non-dominant thigh (quadriceps, hamstring muscles) co-activation decreased between minute 1 and minute 2 by 6% and between minute 1 and minute 3 by 7.2%. Co-activation for the dominant lower leg (tibialis anterior, triceps surae muscles) also decreased between minute 1 and minute 3 by 11.3%. Since no between-day values were measured, it is not clear whether this pattern would change with repeated treadmill walks on different days.

The optimum period for habituation to treadmill walking in this population and whether this differs depending on the measured variable is unknown. Further research is needed with metabolic, co-activation and biomechanical variables to determine whether changes in these variables occur within the 12-15-minute walking practice session, and whether the optimum habituation period is dependent on what is being measured. The minute-by-minute data within a walk suggest that 12-15 minutes of walking practice may be sufficient for habituation when co-activation (considering the last minute of a 3-mintue walk) (Chapter 4) or biomechanical walking economy (Chapter 8) are measured. The effect of repeated treadmill walks on different days, and hence between-day reliability of these measures, however, remains unknown. Since the effect of an intervention may be speed dependent (Maltais et al., 2001), further investigations of this nature should include different speeds. Overall, such information would be useful to researchers who wish to investigate the effect of interventions on these variables.

9.2.2 Generalizability of Treadmill Walking to Over ground Walking

A treadmill walking protocol was used in these studies (Chapters 3, 4, 6-8) because speed could easily be controlled and physiologic (metabolic, cardiorespiratory, thermoregulatory), EMG, and biomechanical data could be easily collected throughout the treadmill walks. Since children and adolescents with CP do not typically walk on a treadmill, it is recognized that the results of these findings from treadmill walking protocols may not completely generalize to over ground walking and thus to the field.

Jeng et al. (1996) found the preferred treadmill walking speed of 7-12 year old children with mild spastic hemiplegic CP after 15-20 minutes of treadmill walking practice was 0.33- 0.89 m s^{-1}, which was markedly slower than their preferred for over ground walking (1.11-1.63 m s^{-1}). Their stride frequencies were also lower on the treadmill (0.83-1.02 strides s^{-1}) compared to over ground (0.90-1.19 strides s^{-1}). The authors attribute this preference toward a lower speed and

stride frequency on the treadmill to the difficulty the child with CP may have walking at a constant speed, as is imposed on the treadmill. They suggest that slower speeds and stride frequencies on the treadmill might make it easier for children with CP to maintain or regain balance in the event of a stumble or other misstep. Healthy children also prefer a significantly lower walking speed and stride frequency on the treadmill compared to over ground, but the difference between the two walking conditions is not so marked (Jeng et al., 1996).

Jeng et al (1996) had only six subjects with CP and six able-bodied subjects in their study. Thus, even though these researchers reported individual data, with such a small sample size it is difficult to determine from this study, for either those with CP or the CON, the nature of the relationship between the child's preferred walking speed over ground and on the treadmill, other than to note the preferred speed for both groups is lower on the treadmill. For example, the strength of the linear correlation, as calculated by this author from the previously published data, between the preferred walking speed on the treadmill and over ground for the CP group, was fairly strong ($r = .69$) but not significant ($P = .1$). This would appear to suggest that there might be a linear relationship between these two variables, but that it was not detected due to the small sample size. This relationship, however, was severely affected by one outlier. With this data point excluded, the strength of the linear relationship was very weak or non-existent ($r = .24$, $P = .7$). For the healthy children, the pattern was similar (Jeng et al., 1996). When the two groups were analyzed as one group, there were no outliers and no significant linear relationship between the preferred speed walking over ground and on the treadmill ($r = .26$, $P = .4$). Since the data of Jeng et al. are inconclusive, likely due to the small sample size, it remains to be determined whether there is a relationship, linear or otherwise, between the children's preferred walking speed on the treadmill and over ground or whether these variables are poorly related.

When healthy 6-7 year old children walk on the treadmill and over ground at the same speed (their over ground CWS), stride frequencies are higher, step widths greater, and stride lengths shorter during treadmill walking compared to over ground walking (Stolze et al., 1997). These authors suggest that their findings indicate the children had more difficulty maintaining balance while walking on the treadmill compared to walking over ground. They go on the suggest that this difficulty with walking balance on the treadmill may be due to an opto-sensory mismatch during treadmill walking, i.e., the proprioceptive information indicates to the children that they are moving, whereas the "visual surround" indicates to them that they are stationary. Such a hypothesis has not been tested in children or adolescents with CP. In the event that proprioceptive information might be compromised in those with spastic CP, due to orthopedic surgery for example, they may rely more on visual cues for balance and thus any opto-sensory mismatch could contribute to their compromised balance when walking on the treadmill.

For healthy adults, the mean O_2 cost of walking on the treadmill compared to over ground is significantly less (4.1-8%), independent of age and walking speed, with the largest difference reported during fast walking (Pearce et al., 1983). The authors attributed their findings to the assistance in forward propulsion that the body received from the treadmill belt motor. The O_2 cost of walking on the treadmill compared to over ground for children, whether able-bodied or with CP, is unknown.

Whether the CP subjects' metabolic, biomechanical walking economy, stride length, or lower limb antagonist muscle co-activation is affected by their walking surface (treadmill or over ground) is also unknown. Since balance appears to be compromised, or more compromised, during treadmill walking than during over ground walking in individuals with CP and in healthy children, the co-activation and stride length reported in Chapter 4 may be higher and shorter, respectively, than those which would occur during an over ground walking

protocol. Increased co-activation in CP has been attributed to the need for increased postural stability (Berger et al., 1984; Brunt and Scarborough, 1988; Crenna et al., 1992). Whether biomechanical walking economy, as measured in the study in Chapter 8 by the BEQ, is affected by the walking surface would likely depend on whether the determinants of walking that are strongly associated with the BEQ are affected by the walking surface. To date it is known that heel rise in terminal stance is a major determinant of minimizing vertical sacral excursion in healthy adults (Della et al., 2001; Kerrigan et al., 2000), but whether this holds true for subjects with CP and whether and to what extent this affects the BEQ (during over ground or treadmill walking) is unknown.

Treadmill-over ground walking differences in metabolic variables, biomechanical walking economy, stride length or lower limb antagonist muscle co-activation variables would be especially relevant if these differences were dependent on the magnitude of the variable in question. Such a relationship could result in a different pattern of inter-subject responses from treadmill protocols compared with those from over ground walking protocols. This would mean that inter-subject or cross-sectional studies using a treadmill walking protocol could not necessarily be compared with data collected in the field. The finding of a significant linear relationship between $\dot{V}O_2$ and BEQ variables collected during treadmill walking and PA variables collected in the field (Chapters 7 and 8) suggests that such $\dot{V}O_2$-walking surface or BEQ-walking surface interactions may not exist or that the strength of such interactions may not be great. For studies that use data that are collected in both the lab and the field as in Chapters 7 and 8, it would be useful to understand how the laboratory protocol, such as walking on the treadmill belt surface, affects the variables in question. Such information would help researchers better understand the limits of comparing lab and field-based measures.

As reviewed in Chapter 1 (Tables 1.2 and 1.3), the O_2 cost of walking is higher for those with CP, compared to able-bodied CON for both walking on the

treadmill and over ground. Thus it is unlikely that the lower walking economy and higher skin and rectal temperatures during treadmill walking in the heat found in the subjects with CP compared to the able-bodied CON (Chapter 6) is due to the treadmill protocol. Whether the walking economy difference between those with CP and CON is affected by the walking surface, however, is unknown. This information would clarify the extent to which the results of the lab-based thermoregulation study described in Chapter 6 can be generalized to the field.

In summary, a basic question remains as to whether the difference (over ground-treadmill) for any variable of interest is merely a shift, or if there is a poor relationship between the two.

9.3 The Frost Co-activation Measure: An Indicator of Motor Control

While more information is needed on the reliability of the Frost CM and the effect on it of the walking surface (see Section 9.2), it shows promise as a global measure of motor control in children and adolescents with mild CP. Stable values can be achieved during treadmill walking after habituation (Chapter 4). The CM is higher in those with mild CP compared to able-bodied children and adolescents (Unnithan et al., 1996b; Unnithan et al., 1996a). For subjects with mild CP, the CM is sensitive to walking speed; values are higher for faster compared to slower speeds (Unnithan et al., 1996b; Unnithan et al., 1996a). In these subjects, their high O_2 cost of walking is associated with a high CM at both the thigh and lower leg (Unnithan et al., 1996a). The CM is also higher on the non-dominant, more involved thigh, than on the dominant, less involved thigh (Chapter 3). The CM at the thigh in those with mild CP is lower than at the lower leg when a one-joint muscle is used to represent the quadriceps (Unnithan et al., 1996b; Unnithan et al., 1996a). When the quadriceps is represented by both one-joint and two-joint muscles (global quadriceps) the CM is higher at the thigh than at the lower leg (Chapter 4). In all cases, the pattern of the CM values for both inter-subject (group) and intra-subject are those one would expect of a measure of motor control in individuals with mild CP. The failure of the CM to distinguish between

the dominant and non-dominant lower legs (Chapter 4) may be a limitation of the measure. It may be that threshold values are needed before the measure is sensitive to dominance. It may also be that, indeed, co-activation at the dominant and non-dominant lower legs is similar.

It has been shown that CM of the right (dominance not assessed) thigh and lower leg correlate with the O_2 cost of walking in those with mild CP (Unnithan et al., 1996a). The relative contribution of the dominant and non-dominant thigh and lower leg, respectively, to inter-subject variability in the O_2 cost has not been studied. Information is also lacking on the modulation of the CM in these subjects. To date it is known that the CM increases with treadmill belt speed (Unnithan et al., 1996b; Unnithan et al., 1996a) and decreases at some sites over the first two minutes of a 3-minute treadmill walk (Chapter 4). This suggests that these subjects are able to modulate co-activation, perhaps in response to postural stability needs, but the extent to which this is possible for them and under what conditions remains unknown.

The finding of higher co-activation at the thigh on the non-dominant compared to dominant side during treadmill walking at FWS in children and adolescents with mild CP (Chapter 4) is contrary to the data of Keefer et al. (2004b). These researchers found no differences between the hemiplegic and non-hemiplegic sides in a group of children and adolescents with mild CP, independent of treadmill belt speed. It might, in fact, be assumed that such intra-subject differences would be greater in those with hemiplegia compared to the subjects with CP tested in Chapter 4, where most had spastic diplegia and only some of them had spastic hemiplegia. Although inter-study differences in subjects and walking protocols can not be ruled out as contributing to inter-study differences in findings, it appears that the patterns of co-activation in those with CP may be dependent, at least to some extent, on the method used to quantify co-activation. In addition to the difference between the results of Keefer et al. and those in Chapter 4, Keefer et al. did not find a relationship between co-activation

at the thigh and the O_2 cost of walking, whereas Unnithan et al. (1996a), who used the same CM as used in Chapter 4, did. The method used by Bowsher et al. (1992) to measure co-activation showed no effect due to speed, whereas that used by Unnithan et al. (1996a) and Damiano et al. (2000) found co-activation to increase with speed. Research comparing the effect of the method used to quantify co-activation on the pattern of the results would help to clarify these seemingly contradictory findings (in the literature).

One limitation of the CM and of any co-activation measure that scales EMG amplitude to the maximum or mean for that muscle is the potential for inflated co-activation values if one of the muscles is much weaker than the other. This limitation to the CM, however, can not explain why Keefer et al. (2004b) did not find intra-thigh differences in co-activation, yet the study detailed in Chapter 4 showed higher thigh co-activation on the non-dominant side. In both studies, EMG amplitude data were normalized to either the mean (Keefer et al., 2004b) or peak (Chapter 4) value during gait and thus the limitation applied in both cases. The patterns of CM found in Chapter 4, with the exception of no difference in the CM between the dominant and non-dominant lower legs, and in the work of Unnithan et al. (1996b; 1996a), are the patterns one would expect for a measure of motor impairment. This suggests that for subjects with mild CP, the effect of an inflated CM may not be marked.

Damiano et al. (2000) recognized the potential of scaling to a peak value to inflate the magnitude of co-activation. These researchers weighted their EMG amplitude data with respect to the relative weakness of the muscle (compared to healthy subjects) in an attempt to account for differences in muscle strength. This method, however, could potentially underestimate the magnitude of co-activation. Weakness in CP has been shown to be in part due to activity of the antagonist muscle (Elder et al., 2003; Wiley and Damiano, 1998). Thus muscle strength will not necessarily reflect the actual level of force output of the muscle. Moreover, the control of muscle activation in gait is believed to be in part reflexive (Duysens

and van de Crommert, 1998), that is, there are somewhat different control mechanisms for muscle activation during gait and during a maximal voluntary contraction of a selected muscle or muscle group. EMG amplitudes in subjects with CP, for example, can be higher during treadmill walking than during a maximal voluntary contraction (Unnithan et al., 1996b; Unnithan et al., 1996a).

Although the potential limitations with normalizing to a peak value have been recognized (Damiano et al., 2000; Lamontagne et al., 2000), no studies to date have systematically assessed the effects of various scaling techniques on co-activation values. Such information would be useful in furthering our understanding of the strengths and limitations of measures that quantify co-activation in children and adolescents with CP.

9.4 The Biomechanical Economy Quotient: A Measure of Walking Proficiency

The BEQ shows potential as a global measure of walking proficiency in those with mild CP. In children and adults with various neurological impairments who walked over ground without support (Kerrigan et al., 1996) and in the subjects with mild CP who walked on the treadmill (Chapter 8), the BEQ was always higher than 1, the approximate value expected for healthy individuals with a mature gait pattern (Kerrigan et al., 1995; Kerrigan et al., 1996). When adults and children with various neurological impairments walked over ground with and without their ankle foot orthoses, the percent change in BEQ due to the use of the braces correlated ($r = .73$) with the percent change in comfortable walking speed due to the braces (Kerrigan et al., 1996). This indicates that the BEQ is sensitive to improvements in gait proficiency in individuals with a neurological impairment. In children and adolescents with mild spastic CP, a negative, linear relationship was found (Chapter 8) between the BEQ and movement count data (accelerometer), indicating that higher biomechanical walking economy is associated with a higher level of habitual PA. The BEQ was also found to be

stable during treadmill walking at various speeds in children and adolescents with CP (Chapter 8).

As noted in Section 9.21, further information on the reliability of the BEQ is needed to enhance understanding of its utility as an outcome measure. More information is also needed on the effect of walking speed on the BEQ. The data in Chapter 8 suggest that the effect of walking speed on the BEQ is dependent on the BEQ value (or average value across the speeds tested). For subjects with a BEQ of greater than approximately 2, a value of 2 being double that of the "norm", their biomechanical walking economy improved with faster speeds. The opposite pattern was found for subjects with a BEQ of less than about 2. Whether a BEQ of 2 indicates some threshold level of impairment or proficiency, or whether the effect of walking speed is perhaps an artifact of the method (treadmill walking) requires further research (over ground and on the treadmill) with larger sample sizes, a variety of walking speeds, and with subjects with differing BEQ values. Since the BEQ is a measure of biomechanical walking economy and thus mechanical energy conservation, it would also be useful to know if the BEQ correlates with metabolic energy consumption, perhaps $\dot{V}O_2$ per kg per stride, and whether this relationship is affected by walking speed or surface (treadmill vs. over ground). Overall, the data gained from these research suggestions would lead to a better understanding of the strengths and limitations of the BEQ as a measure of biomechanical walking economy or global movement impairment during walking.

When vertical excursion of the modeled COM (sacrum) of actual gait is considered, heel rise accounts for about 2/3 of the total reduction (Della et al., 2001). Pelvic rotation, pelvic obliquity, and knee flexion during stance are of minor importance (Della et al., 2001; Gard and Childress, 1997; Gard and Childress, 1999). Heel rise raises the COM at its lowest point and thus reduces its overall vertical excursion (Kerrigan et al., 2000). It is unknown what determinants affect vertical excursion of the COM in those with CP. Information

on the effect on the BEQ in CP of various gait determinants would be of value to researchers and clinicians interested in improving walking proficiency in this population. This could lead to a better understanding, for example, of how interventions such as ankle foot orthoses improve both metabolic walking economy (Maltais et al., 2001) and biomechanical walking economy as determined by the BEQ (Kerrigan et al., 1996).

9.5 Thermoregulation

The findings in Chapters 5 and 6 suggest that thermoregulatory mechanisms may not impaired in children and adolescents with mild CP (at least at the exercise intensity used in Chapter 5), but rather that, when these subjects walk at the same speed and slope in the heat as able-bodied children and adolescents, their body temperatures become higher than those of CON because they produce more metabolic heat. To the best of this author's knowledge, there are no previously published studies of the thermoregulatory responses of children and adolescents with CP during exercise in the heat. For able-bodied boys exercising in a hot, dry environment, it has been suggested (Falk, 1998) that age-related differences in walking economy may explain the higher rectal temperatures, skin temperatures, and HR of the younger compared with older subjects reported during treadmill walking (Wagner et al., 1972), but not during cycling (Falk et al., 1992b). During walking on the treadmill, younger boys are less economical walkers than older boys and hence produce more metabolic heat (Frost et al., 2002). During cycling, however, metabolic rates are similar between the groups (Falk et al., 1992b). It remains unknown, however, the extent to which the findings from Chapter 5 are valid for higher exercise intensities. In other words, if both groups worked at the same metabolic rate as did the CP group in Chapter 6, would there be differences between the two groups in thermal strain? It is possilbe that the intensity of the exercise in Chapter 5 was insufficient to elicit intergroup differences in thermal strain.

As appropriate for the first exercise studies in the heat with this (CP) population, the thermoregulation studies (Chapters 5 and 6) were performed under very controlled conditions in the lab. It is unknown whether the increased heat load that those with CP could potentially have to dissipate if they walk or run at the same speed as their peers affects their function. Potential situations where their low walking economy and higher heat load could be relevant would be a summer school or day care outing to a zoo or amusement park on a hot summer day. Such venues require long walks in the heat and the situation calls for the children and adolescents with mild CP to "keep up" with their peers. Other situations would be a sporting event on a hot summer day. Since the children and adolescents in question are those with mild CP they could presumably compete with able-bodied children or even among themselves. The findings in Chapter 6 do not suggest that those with CP are at risk for heat-related illness as the core (rectal) temperatures were not dangerously high (> 39 °C). Whether added heat load and thermoregulatory strain affects physical performance or enjoyment of the activity is also unknown. Information from field studies on these subjects' thermoregulatory responses, level of PA, and perception of heat and comfort is required to determine more fully the practical implications of the findings in Chapters 5 and 6.

9.6 Habitual Physical Activity

Although it is known that ambulatory children with CP have reduced habitual PA compared to CON (van den Berg-Emons et al., 1995), there are, to the best of this author's knowledge, no previously published information on explanations for this reduced PA. The studies described in Chapters 7 and 8 suggest that that the low PA of those with mild CP may be related to their high O_2 cost of walking and low biomechanical walking economy. These studies, however, are more exploratory than definitive in nature. They provide information for the basis of future, more definitive research regarding mechanisms related to low PA in these subjects.

Future cross-sectional studies, investigating associations such as those in Chapters 7 and 8, should employ larger sample sizes. This would help to ensure that the relationships found are stable. As well, with larger sample sizes, more complex analyses of associations between the variables can be performed. Frost et al. (2002), for example, used a multi-disciplinary approach to explain inter-age differences in the O_2 cost of walking per kg body mass in 30 healthy children and adolescents. Using a multiple regression approach, they showed that age and lower limb antagonist muscle co-activation were important predictors of the O_2 cost of walking, but that total body mechanical power was not. Such an approach could be used to determine what factors, besides the O_2 cost of walking and biomechanical walking economy, contribute to the levels of PA in children and adolescents with CP. In able-bodied young people, low socio-economic status (Wold and Anderssen, 1992) and geographic location (Sallis et al., 1990) affect PA. The effect of such factors on PA in those with CP is unknown. Their perceptions may also play a role. Fifty percent of adolescents with CP who completed a recently published province wide Ontario survey considered themselves less fit than their able-bodied peers (Longmuir and Bar-Or, 2000).

The patterns of PA over time are also unknown for those with CP. In the studies in Chapters 7 and 8, age was not related to PA, as the age-range was relatively narrow. In healthy, able-bodied individuals, PA declines with age, with the greatest decline being during adolescence (Caspersen et al., 2000; Sallis, 1993; Telama and Yang, 2000; van Mechelen et al., 2000). Interestingly, a cross-sectional study of the O_2 cost of walking in children and adolescents with spastic diplegic CP showed that this cost increased with age (Campbell and Ball, 1978). Since it was shown in Chapter 7 that low PAL is associated with a high O_2 cost of walking for those with CP, if these individual's O_2 cost of walking increases with age, then their habitual PA, as it does for healthy children and adolescents, may decrease with age.

The low levels of PA in those with CP could create health concerns. It has been shown that able-bodied Canadian children are becoming progressively more overweight and obese (Tremblay and Willms, 2000), and that being overweight is associated with inactivity (Tremblay and Willms, 2003). Should this be the case for those with CP whose walking is already compromised, such a relationship could have marked deleterious effects (low walking economy leads to low PA, leads to increased weight, leads to further decreases in walking economy, leads to further decreases in PA....). Aerobic exercise training may increase the level of PA in those with CP (trend for changes before and after training, P=.07) (van den Berg-Emons RJ et al., 1998). Such a finding is promising and warrants further investigation. The effect of other interventions on these subjects' PA is unknown. Interventions such as ankle foot orthoses, that have been previously shown to improve metabolic (Maltais et al., 2001) and biomechanical (Kerrigan et al., 1996) walking economy, also merit investigation as to their effects on PA. Data to show that an improvement in walking economy is associated with an increase in PA would strengthen the potential for a causal relationship between these two variables.

9.7 Conclusions

The overall hypothesis that guided this research was that the high energy cost of walking in children and adolescents with mild spastic CP would have specific physiologic (metabolic, cardiorespiratory, thermoregulatory), electromyographic, and biomechanical implications. This hypothesis proved correct.

From a physiologic perspective, reliable metabolic and cardiorespiratory data were collected during treadmill walking. These subjects' high O_2 cost of treadmill walking also resulted in higher body temperatures than in the able-bodied CON during treadmill walking exercise in the heat and was negatively associated with their level of PA (measured using HR calibrated to $\dot{V}O_2$).

From an electromyographic perspective, stable lower limb antagonist muscle co-activation (a measure which was previously shown to be associated with the O_2 cost of walking in CP), was obtained by the 2nd minute of a 3-minute fast walk. Co-activation was also higher at the non-dominant, more involved thigh than at the dominant thigh.

From a biomechanical perspective, biomechanical walking economy was stable minute-by-minute throughout a 3-minute treadmill walk, independent of speed. Stride length, measured during fast walking was stable by the 2nd minute of a 3-minute walk. Habitual PA, measured mechanically, was negatively associated with biomechanical walking economy.

In summary, the results from the experiments conducted for this thesis contribute to our knowledge of the implications of the high energy cost of walking in children and adolescents with mild CP from a multi-disciplinary perspective, and should guide future research regarding relevant measurement tools, mechanisms, and interventions.

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APPENDIX: QUESTIONNAIRES AND SELECTED DATA SETS

A.1 Questionnaires

A.1.1 Introductory Visit Questionnaire

Subject #: _____
Date & Time: _____

Pre-test Questionnaire (IntroVisit)

Please answer the following questions about your child as well as you can. We will be happy to explain any questions that are unclear to you. Please use the other side of the sheet if necessary.

1. Does your child have any ***chronic medical condition(s)***? YES NO
   If yes, please **list** the condition(s).
   _____
   _____
   _____

2. Please list ***all medication*** that your child has taken in the last 3 days:

Medication	How Often	Quantity

3. Has your child participated in ***heavy exercise*** within the past ***8 hours***? YES NO

4. Has there been a ***change in your child's level of physical activity this past week*** (more/less active; more/less time resting)? YES NO

5. If yes, ***list any illness or circumstances*** over the ***last week*** that have resulted in this change and ***describe the change*** in physical activity.

Reason for Change in Physical Activity	Description of Change in Physical Activity

6. Has your child complained of any ***pain or discomfort*** in the ***neck, arms, back, or legs*** over the last week?
   YES NO

7. If yes, please describe the ***type of pain*** (dull sharp, ache), ***location***, ***how often***, ***how long*** it lasts and ***what brings it on***.

Location & Type of Pain or Discomfort	How Often/How long Does It Last?	What Brings It On?

8. Has your child had any ***caffeine*** (coffee, tea, coke, pepsi, or chocolate) within the past 3 hours? YES NO

9. When did you child ***complete their last meal***? Time: _____

10. Please list the items you child ate in ***their last meal***?

Item	Quantity

11. Has your child had any ortthopedic (bone or muscle) surgery within the last year? YES NO
If so, please state: WHERE _____
WHEN (month) _____

Surgical History

1. Has your child had a selective dorsal rhizotomy? Yes No, If yes, please state year of surgery. _____
2. Has your child had orthopedic surgery? If yes state type and year (below)

Type	Year

Botox

1. Has your child had Botox injections? If yes, for the last injections state where and when

Other Medication

1. Is your child on any other medication to reduce spasticity?
2. If yes, state name of medication. _____

Notification of Family Doctor

McMaster University requires that we notificy your family doctor of your child's participation in this study. Please state your family doctor's name and contact information (telephone number, address), below. If your child does not have a family doctor, please substitute the doctor who is most involved in your child's care.

Name of Doctor _____

Address _____

_____

Telephone # _____

Interviewer:_____

A.1.2 Physical Activity Questionnaire I: Chapters 3-6

Subject #: _____
Date & Time: _____

Physical Activity Questionnaire

Please circle the most appropriate answer:

1. To get around **indoors**, I usually:
   - **A** crawl
   - **B** walk by myself
   - **C** walk using a walker or canes
   - **D** use my wheelchair
   - **E** have someone push my wheelchair or carry me

   Details

   _____
   _____

2. To get around **outside** I usually:
   - **A** walk by myself
   - **B** walk using a walker or canes
   - **C** use my wheelchair
   - **D** have someone push my wheelchair

   Details

   _____
   _____

3. I am:
   - **A** **just as** physically active as my friends
   - **B** **more** physically active than my friends
   - **C** **less** physically active than my friends
   - **D** not sure, I can't compare myself to my friends

   Details

   _____
   _____

4. I am:
   - **A** **just as** physically fit as my friends
   - **B** **more** physically fit than my friends
   - **C** **less** physically fit than my friends
   - **D** not sure, I can't compare myself to my friends

   Details

   _____
   _____

5. I am:
   - **A** **just as** physically fit as my brother(s)/sister(s)
   - **B** **more** physically fit than my brother(s)/sister(s)
   - **C** **less** physically fit than my brother(s)/sister(s)
   - **D** not sure, I can't compare myself to my brother(s)/sister(s)
   - **E** an only child, I do not have brother(s)/sister(s)

   Details

6. In gym class I:
   - **A** **always** do what my classmates are doing
   - **B** **sometimes** do what my classmates are doing
   - **C** **never** do what my classmates are doing
   - **D** do not take gym

   Details

7. If you are **limited** in physical activity at school, for what reasons? (You may fill in more than one answer):
   - **A** Advice of doctor
   - **B** Advice of teacher
   - **C** Decision of parents
   - **D** I do not want to participate
   - **E** Other

   Details

8. What I **mostly** do after school is:
   - **A** do my homework
   - **B** watch TV or play video games
   - **C** listen to music or read
   - **D** go outside
   - **E** play games where I run, walk or crawl a lot

   Details

9. Are you a member of a **sports team** at school or elsewhere?
   - **A** No
   - **B** Yes, with school (intramural)
   - **C** Yes, other
   - **D** Yes, in the past, but not any longer

   Details

10. If you **train regularly**, what is the nature of your training?

Type of Sport	Hours/Week	Time of Year	Comments

11. Are there any **other members of your family** who participate in **competitive sports?**
    - **A** No, no one in the family
    - **B** Yes

12. If "Yes", please describe:

Family Member	Type of Sport	Trains Regularly?

13. Do you participate in any **recreational activity** that requires physical effort? (For example; swimming, riding a bicycle or tricycle, gymnastics. dancing, karate. Skating, skiing):

Type of Activity	Time of Year	Hours/Week

14. Does any **member of the family** participate in **recreational activities** that require physical effort?
    - **A** Yes
    - **B** No one

15. If "yes", please specify:

Family Member	Type of Activity	Time of Year

16. Do you have any **difficulty** during or after physical exertion?
    - **A** No complaint
    - **B** Shortness of breath
    - **C** Pain (Identify where)_____
    - **D** Fatigue (After how long?) _____
    - **E** Other (Please specify what the difficulty is)_____

    Details

    _____

    _____

17. Do you often sustain **bruises, injuries, or other damage** when physically active?
    - **A** Yes
    - **B** No

18. If yes, please specify

_____

19. In your opinion, are you as active as you should be?
    - **A** Yes
    - **B** Too active
    - **C** Not active enough

    Details

    _____
    _____

20. If you are not as active as you should be, what in your opinion is the reason? (You can circle more than one answer)
    - **A** Lack of interest
    - **B** Cerebral Palsy or other condition
    - **C** Lack of suitable place to be active
    - **D** Other
    - **E** I don't know

    Details

    _____
    _____

21. Please circle any of the following statements that you agree with (you can circle more than one statement):
    - **A** Physical activity is important because it is fun
    - **B** Physical activity is necessary to keep fit
    - **C** Physical activity is good for health reasons
    - **D** Physical activity may be dangerous to one's health
    - **E** Physical activity can prevent overweight
    - **F** Physical activity is important mostly to people who want to become professional athletes

Thank you

Form was filled out by: _____

A.1.3 Physical Activity Questionnaire II: Chapters 7 and 8 (Weekday)

Subject ID _____
Date _____
Lower Limb Dominance _____

Interview (Weekday)

Activity	Clock Time Yes/No	Comments
RISING FROM BED		
Stairs to main floor	**Yes/No**	
Breakfast?	**Yes/No**	
TRANSPORT TO SCHOOL		
Walk/Cycle to school	**Yes/No**	**How far (blocks) to school?** _____ How long is the walk, cycle? _____
Drive/Bus to school	**Yes/No**	
Stairs to classroom?	**Yes/No**	
ACTIVITY AT SCHOOL (MORNING)		
Spare period/recess	**Yes/No**	**Leave school ground (how far)?** _____
Activities outside of home room (name the ones today)?	**Yes/No**	
LUNCH TIME		
Lunch room (stairs)	**Yes/No**	
Recess/leave school	**Yes/No**	**How far (blocks) to school?** _____ How long is the walk, cycle? _____

Activity	Clock Time Yes/No	Comments
ACTIVITY AT SCHOOL (AFTERNOON)		
Spare period/recess	**Yes/No**	**Leave school ground (how far)? _____**
Activities outside of home room (name the ones today)?	**Yes/No**	
TRANSPORT HOME		
Walk/Cycle home	**Yes/No**	**How far (blocks) to school? _____** How long is the walk, cycle? _____
Drive/Bus to home	**Yes/No**	
AFTER SCHOOL (BEFORE SUPPER)		
Home work?	**Yes/No**	
TV/computer	**Yes/No**	
Outside (free play)	**Yes/No**	
After school activity	**Yes/No**	Name activity _____ If physical activity for how long? _____
Walk/cycle to activity	**Yes/No**	
Drive to activity	**Yes/No**	
SUPPER		In front of TV/computer Yes/No
AFTER SUPPER		
Home work?	**Yes/No**	
TV/computer	**Yes/No**	
Outside (free play)	**Yes/No**	

Activity	Clock Time Yes/No	Comments
After school activity	**Yes/No**	Name activity _____ If physical activity for how long? _____
Walk/cycle to activity	**Yes/No**	
Drive to activity	**Yes/No**	
BEFORE BED		
Bathroom?	**Yes/No**	
Other?	**Yes/No**	

How typical a week day was this? What was typical? What was atypical?

A.1.4 Physical Activity Questionnaire II: Chapters 7 and 8 (Weekday)

Subject ID _____
Date _____
Lower Limb Dominance _____
Interview (Weekend)

Activity		Time	Comments
Rising from bed			
Stairs to main floor	**Yes/No**		
Breakfast?	**Yes/No**		
#1 ACTIVITY (MORNING)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____
Other comments			
#2 ACTIVITY (MORNING)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____
Other comments			
#3 ACTIVITY (MORNING)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____

Activity		Clock Time Yes/No	Comments
Other comments			
LUNCH Time			
#1 ACTIVITY (AFTERNOON)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____
Other comments			
#2 ACTIVITY (AFTERNOON)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____
Other comments			
#3 ACTIVITY (AFTERNOON)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____
Other comments			
SUPPER			In front of TV/computer Yes/No
#1 ACTIVITY (AFTERSUPPER)			Name activity _____ If physical activity for how long? _____
Transport to activity	**Yes/No**		
Walk/cycle to activity	**Yes/No**		How far? _____

Activity		Clock Time Yes/No	Comments
Other comments			
#2 ACTIVITY (AFTERSUPPER)			Name activity _____ If physical activity for how long? _____
Transport to activity	Yes/No		
Walk/cycle to activity	Yes/No		How far? _____
Other comments			
#3 ACTIVITY (AFTERSUPPER)			Name activity _____ If physical activity for how long? _____
Transport to activity	Yes/No		
Walk/cycle to activity	Yes/No		How far? _____
Other comments			
BEFORE BED			
Bathroom?	Yes/No		
Other?	Yes/No		Name activity _____ If physical activity for how long? _____
Other comments			

How typical a weekend day was this? What was typical? What was atypical?

_____

_____

_____

A.2 Selected Data Sets

A.2.1 Chapter 3

	Treadmill Belt Speed, m/s			Rest	Absolute Oxygen Uptake, l/min								
	60	75	90	VO2	D1	D2	D3	D1	D2	D3	D1	D2	D3
Sub#	FWS	FWS	FWS	l/min	60	60	60	75	75	75	90	90	90
1	0.7	0.9	**1.1**	0.16	0.36	0.37	0.37	0.43	0.47	0.41	0.52	0.55	0.49
2	**1.1**	1.4	1.6	0.13	0.61	0.53	0.47	0.62	0.69	0.61	0.91	0.95	0.83
3	0.3	0.4	0.5	0.19	1.13	1.31	1.06	1.12	1.33	1.19	1.14	1.35	1.16
4	0.9	1.1	1.4	0.14	0.38	0.38	0.43	0.43	0.40	0.28	0.56	0.62	0.63
5	0.3	0.3	0.4	0.21	0.52	0.51	0.47	0.49	0.52	0.53	0.57	0.54	0.50
6	1.3	1.6	2.0	0.27	1.13	1.23	1.15	1.58	1.64	1.59	2.37	2.33	2.16
7	0.9	1.2	1.4	0.13	0.43	0.54	0.44	0.55	0.62	0.58	0.77	0.88	0.78
8	0.8	1.0	1.3	0.19	0.50	0.50	0.53	0.46	0.59	0.60	0.79	0.71	0.73

	Absolute Ventilation, l/min						Absolute Heart Rate, beats/min											
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
Sub#	60	60	60	75	75	75	90	90	90	60	60	60	75	75	75	90	90	90
1	11.9	13.0	12.3	14.9	15.1	19.1	17.9	17.7	19.0	107	108	97	113	118	116	122	120	121
2	16.2	17.5	14.0	19.4	20.5	20.2	27.3	32.0	26.1	106	110	116	117	112	125	149	136	141
3	35.9	47.8	33.9	36.4	43.8	36.7	42.5	47.7	36.9	162	174	156	167	173	162	173	182	163
4	11.4	13.8	13.9	15.3	14.0	10.7	22.0	20.3	22.1	128	130	123	138	133	129	154	152	149
5	17.8	15.6	17.1	17.1	19.3	18.8	22.1	19.0	17.5	111	102	102	110	99	101	116	98	99
6	32.1	34.6	32.8	44.1	46.8	46.0	81.6	77.9	67.7	125	116	122	138	126	135	170	160	157
7	13.8	17.5	15.5	17.4	18.9	19.6	24.4	28.4	25.8	122	127	119	133	130	128	157	154	145
8	18.7	17.4	17.5	16.6	20.0	18.6	27.6	23.4	21.1	116	120	110	120	127	120	127	135	128

A.2.2 Chapter 4

Treadmill Belt Speed, m/s																
Sub#	90	DOM	Thigh		NDOM	Thigh		DOM	Lower	Leg	NDOM	Lower	Leg	Stride	Length, m	
Sub#	FWS	Min1	Min2	Min3	Min1	Min2	Min3	Min1	Min2	Min3	Min1	Min2	Min3	Min1	Min2	Min3
1	1.1	29.78	32.83	30.53	32.93	30.66	31.07	26.98	25.39	24.57	17.16	16.99	17.40	0.99	0.99	0.98
2	1.6	23.53	22.47	22.30	35.43	34.11	32.47	25.86	23.87	23.20	23.72	23.04	22.75	1.45	1.47	1.49
3	0.5	43.90	41.80	40.57	46.00	44.39	45.20	43.60	39.03	37.48	24.90	24.40	24.50	0.53	0.56	0.55
4	1.4	21.38	22.05	21.98	38.76	36.85	36.22	17.36	14.56	13.18	24.30	23.71	23.69	1.13	1.15	1.17
5	0.4	37.00	34.30	32.76	33.64	32.76	32.78	24.79	23.88	22.90	29.16	28.51	28.46	0.64	0.64	0.63
6	2.0	38.45	35.80	37.48	39.91	35.60	34.74	24.86	24.70	24.93	27.48	28.40	28.75	1.58	1.59	1.59
7	1.4	15.04	13.32	12.80	34.07	32.85	31.75	20.48	18.54	17.52	26.70	24.74	24.36	1.15	1.18	1.19
8	1.3	15.11	14.85	14.12	29.97	26.12	25.63	20.11	19.18	17.27	25.91	25.92	26.28	1.06	1.08	1.10

A.2.3 Chapter 5

	Oxygen Uptake l/min			Exercise Heart Rate Beats/min			Recovery Heart Rate Beats/min			Sweatig Rate
Sub#	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**	**g/m2/h**
01CP	0.70	0.76	0.79	113	120	125	25	26	30	239.6
01CON	0.67	0.66	0.73	123	121	121	19	17	22	129.6
02CP	0.38	0.44	0.42	128	131	134	25	30	25	208.0
02CON	0.45	0.45	0.47	137	137	136	34	34	41	168.0
03CP	0.43	0.39	0.40	132	134	131	14	14	17	81.1
03CON	0.43	0.42	0.44	110	106	106	22	11	24	115.9
04CP	0.52	0.53	0.63	116	120	123	20	21	19	219.8
04CON	0.44	0.56	0.54	104	116	120	19	20	22	229.6
05CP	0.26	0.22	0.28	119	131	131	18	21	24	131.4
05CON	0.16	0.17	0.16	126	123	120	14	20	10	105.9
06CP	0.42	0.38	0.41	116	125	127	28	14	25	127.1
06CON	0.49	0.43	0.42	110	105	105	24	15	20	110.8
07CP	0.48	0.50	0.54	127	128	125	42	41	46	137.1
07CON	0.66	0.67	0.70	150	150	152	29	30	38	191.8
08CP	0.73	0.77	0.71	114	118	113	15	17	19	215.9
08CON	0.54	0.55	0.53	111	113	111	18	25	24	221.9
09CP	0.38	0.38	0.39	117	120	120	8	12	16	173.5
09CON	0.34	0.34	0.35	120	122	122	22	21	22	169.7
10CP	0.61	0.55	0.61	123	121	124	21	18	26	190.2
10CON	0.73	0.81	0.76	135	135	138	22	25	26	204.5
11CP	0.44	0.40	0.47	123	121	119	15	13	19	162.5
11CON	0.43	0.42	0.39	134	131	125	18	17	6	193.3

A.2.4 Chapter 5 (continued)

Time, min	-5	0	10	14	23	30	34	43	50	54	-5	0	10	14	23	30	34	43	50	54
Sub#	Rectal Temperature, degrees Celcius										Skin Temperature, degrees Celcius									
01CP	37.5	37.5	37.5	37.5	37.6	37.6	37.6	37.7	37.6	37.7	33.9	35.5	36.1	36.2	35.9	36.1	36.0	35.7	36.0	36.0
01CON	36.9	37	37.1	37.1	37.1	37.1	37.2	37.2	37.2	37.3	31.9	33.9	35.0	35.4	35.5	35.4	35.2	35.0	34.9	35.4
02CP	37.4	37.4	37.4	37.5	37.4	37.5	37.5	37.5	37.6	37.6	32.5	35.7	35.7	35.8	35.7	35.8	35.8	35.6	35.7	35.7
02CON	37.2	37.3	37.3	37.4	37.3	37.3	37.4	37.3	37.3	37.4	30.9	33.6	35.1	35.6	35.4	35.7	35.8	35.2	35.5	35.6
03CP	37.5	37.6	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.6	31.5	34.2	35.1	35.3	35.5	35.7	35.7	35.6	35.5	35.7
03CON	37.5	37.6	37.4	37.3	37.2	37.2	37.2	37.3	37.4	37.3	30.7	33.2	35.0	35.3	35.6	35.6	35.7	35.5	35.6	35.5
04CP	37.7	37.8	37.7	37.7	37.7	37.7	37.7	37.6	37.7	37.7	32.0	33.4	35.4	35.8	35.6	36.0	36.1	36.0	36.0	36.1
04CON	37.3	37.3	37.2	37.2	37.3	37.3	37.3	37.4	37.3	37.4	32.5	34.1	35.2	35.7	36.0	36.4	36.4	36.3	36.2	36.1
05CP	37.2	37.3	37.2	37.2	37.2	37.3	37.3	37.4	37.4	37.5	33.1	34.1	35.6	35.8	35.9	35.7	35.9	35.5	35.7	35.5
05CON	37.6	37.6	37.5	37.4	37.3	37.3	37.3	37.3	37.3	37.3	31.1	33.6	35.3	35.5	35.6	35.6	35.6	35.6	35.8	35.7
06CP	37.4	37.5	37.5	37.5	37.4	37.5	37.5	37.5	37.6	37.6	34.1	35.6	35.9	36.0	35.6	35.9	35.8	35.7	35.7	35.7
06CON	37.4	37.5	37.5	37.5	37.4	37.4	37.4	37.5	37.5	37.5	31.5	33.7	35.4	35.5	35.4	35.7	35.6	35.5	35.5	35.5
07CP	37.7	37.8	37.7	37.8	37.7	37.7	37.7	37.7	37.7	37.7	33.3	35.0	35.9	36.1	35.8	35.9	35.9	35.8	35.9	35.8
07CON	37.3	37.5	37.5	37.7	37.6	37.6	37.7	37.6	37.6	37.7	31.4	33.1	35.6	35.8	35.5	35.7	35.4	35.3	35.7	35.2
08CP	37.7	37.6	37.5	37.5	37.5	37.4	37.4	37.4	37.4	37.4	31.2	33.0	35.0	35.2	35.7	35.8	35.8	35.5	36.0	36.0
08CON	37.5	37.6	37.6	37.6	37.6	37.5	37.5	37.5	37.5	37.6	30.9	33.0	35.2	35.9	35.9	36.2	36.1	36.1	36.0	36.1
09CP	37.6	37.6	37.5	37.5	37.4	37.4	37.4	37.4	37.3	37.3	31.2	33.1	35.6	35.7	35.8	35.7	35.9	35.6	35.8	35.8
09CON	37.5	37.5	37.4	37.3	37.4	37.3	37.4	37.4	37.4	37.3	32.7	34.7	35.7	35.7	35.6	35.9	36.0	35.6	35.8	35.8
10CP	37.3	37.5	37.5	37.5	37.4	37.4	37.5	37.4	37.5	37.5	32.0	33.3	34.7	35.0	35.1	35.6	35.4	35.5	35.4	35.5
10CON	37.6	37.6	37.5	37.5	37.5	37.5	37.5	37.4	37.5	37.5	33.1	35.1	36.2	36.0	35.7	35.9	35.7	35.6	35.7	35.6
11CP	37.3	37.3	37.3	37.4	37.5	37.5	37.5	37.5	37.4	37.5	32.6	33.7	35.7	35.7	35.7	35.8	35.7	35.5	35.7	35.8
11CON	37.7	37.8	37.8	37.8	37.7	37.7	37.7	37.5	37.5	37.5	32.9	34.2	35.8	36.1	35.8	36.1	35.9	35.7	35.9	35.8

A.2.5 Chapter 6

	Oxygen Uptake l/min			Ex. Heart Rate Beats/min			Sweatig Rate	Chamber Time, min 7.8	15.5	28.8	36.5	49.5	57.3
Sub#	B1	B2	B3	B1	B2	B3	g/m2/h	Rating of Perceived Exertion arbitrary units					
01CP	0.62	0.61	0.59	133	138	137	222.5	7	11	12	14	13	15
01CON	0.37	0.39	0.37	107	117	116	136.7	9	9	9	9	9	9
02CP	1.33	1.67	1.70	123	148	154	285.0	9	11	9	13	11	13
02CON	0.80	1.10	1.10	93	107	112	263.1	12	12	11	11	12	11
03CP	0.75	0.80	0.78	140	150	154	134.3	9	9	9	9	9	9
03CON	0.47	0.48	0.46	92	95	100	35.7	7	7	7	7	7	7
04CP	0.64	0.64	0.63	141	145	151	140.7	9	11	11	10	11	11
04CON	0.58	0.59	0.60	132	151	158	155.9	15	13	15	17	15	17
05CP	0.73	0.92	0.94	145	165	174	166.0	11	13	13	13	12	11
05CON	0.52	0.72	0.73	97	111	112	271.6	7	8	11	12	12	12
06CP	0.92	0.88	0.87	140	144	146	180.3	12	12	12	11	12	11
06CON	0.72	0.71	0.72	122	122	123	225.9	9	11	12	12	12	12
07CP	0.86	0.82	0.77	160	160	160	150.3	12	12	11	11	12	11
07CON	0.50	0.52	0.52	112	112	109	132.9	12	13	13	13	13	13
08CP	0.51	0.45	0.43	153	149	148	192.7	14	15	14	15	13	13
08CON	0.38	0.37	0.40	93	93	98	217.4	8	8	8	9	8	9
09CP	0.81	0.81	0.67	149	161	169	170.1	15	17	17	19	17	19
09CON	0.55	0.54	0.56	117	120	118	234.9	11	9	9	9	9	9
10CP	1.24	1.20	1.22	148	154	157	175.3	15	15	17	15	16	15
10CON	0.78	0.79	0.79	110	114	111	197.6	14	14	13	13	12	13

A.2.6 Chapter 6 (continued)

Chamber														
Time														
min	-3	5	11	16	21	26	32	37	42	47	53	58	63	68
Sub#	**Rectal Temperature, degrees Celcius**													
01CP	37.40	37.40	37.40	37.46	37.40	37.40	37.51	37.56	37.51	37.51	37.56	37.56	37.51	37.51
01CON	37.35	37.24	37.14	37.19	37.08	37.03	37.08	37.14	37.14	37.14	37.24	37.35	37.40	37.35
02CP	37.35	37.35	37.46	37.51	37.56	37.51	37.56	37.72	37.78	37.78	37.89	37.99	38.10	37.99
02CON	37.24	37.30	37.24	37.24	37.24	37.19	37.19	37.24	37.30	37.30	37.30	37.40	37.40	37.40
03CP	37.51	37.46	37.40	37.51	37.56	37.56	37.62	37.72	37.78	37.78	37.83	37.89	37.89	37.89
03CON	37.03	37.03	37.03	37.03	36.92	36.98	37.03	37.08	37.14	37.08	37.08	37.08	37.14	37.19
04CP	37.46	37.35	37.40	37.51	37.56	37.56	37.62	37.72	37.67	37.67	37.78	37.89	37.83	37.78
04CON	37.46	37.40	37.59	37.60	37.60	37.71	37.75	37.75	37.75	37.78	37.83	37.89	37.85	37.78
05CP	37.56	37.56	37.62	37.67	37.72	37.72	37.89	37.99	38.10	38.10	38.15	38.32	38.26	38.21
05CON	37.40	37.35	37.35	37.35	37.40	37.40	37.46	37.51	37.56	37.56	37.56	37.67	37.67	37.67
06CP	37.46	37.46	37.46	37.56	37.67	37.67	37.72	37.83	37.89	37.89	37.94	37.99	38.05	37.99
06CON	37.35	37.30	37.30	37.40	37.46	37.40	37.46	37.56	37.62	37.56	37.62	37.72	37.67	37.62
07CP	37.46	37.46	37.46	37.46	37.51	37.56	37.62	37.56	37.67	37.67	37.73	37.75	37.77	37.78
07CON	37.46	37.46	37.46	37.46	37.51	37.46	37.46	37.46	37.46	37.40	37.46	37.46	37.46	37.46
08CP	37.51	37.51	37.51	37.62	37.62	37.62	37.67	37.72	37.78	37.72	37.78	37.78	37.78	37.72
08CON	37.51	37.56	37.67	37.67	37.62	37.56	37.62	37.62	37.62	37.56	37.56	37.56	37.56	37.56
09CP	37.51	37.51	37.67	37.89	37.72	37.67	37.94	38.10	38.05	37.99	38.10	38.21	38.21	38.10
09CON	37.72	37.72	37.72	37.72	37.62	37.62	37.56	37.62	37.56	37.51	37.51	37.51	37.51	37.46
10CP	37.30	37.30	37.35	37.40	37.46	37.40	37.51	37.56	37.67	37.72	37.72	37.78	37.83	37.89
10CON	37.24	37.19	37.14	37.24	37.35	37.40	37.35	37.46	37.51	37.56	37.46	37.51	37.56	37.56

	-3	5	11	16	21	26	32	37	42	47	53	58	63	68
	Skin Temperature, degrees Celcius													
	33.69	35.44	35.62	35.25	35.76	36.08	35.74	35.78	35.52	35.48	35.37	35.47	35.04	35.00
	31.74	34.24	34.80	35.25	35.55	35.66	35.73	35.79	35.84	35.89	35.68	35.41	35.27	35.45
	31.83	34.10	34.77	35.03	35.10	35.43	34.98	35.09	35.36	35.05	34.74	35.02	35.43	34.89
	32.55	34.43	34.89	34.72	34.45	34.72	34.31	33.93	33.87	33.91	33.77	33.93	33.73	33.62
	32.37	34.82	35.48	35.77	35.78	36.07	36.04	36.41	35.87	35.92	36.22	36.34	35.75	35.78
	32.19	34.40	34.61	34.70	34.82	34.92	34.68	34.60	34.83	34.82	34.67	34.45	34.70	34.83
	32.71	34.96	35.52	35.50	35.54	35.64	35.64	35.70	35.55	35.61	35.63	35.75	35.68	35.56
	32.74	35.03	35.57	35.52	35.72	35.97	35.96	36.00	35.97	35.77	35.74	36.10	36.21	36.22
	31.54	34.27	35.31	35.63	35.63	35.50	35.75	35.94	35.97	35.76	35.99	36.07	35.96	35.84
	33.39	34.74	34.94	35.19	35.30	35.32	35.28	35.52	35.39	35.39	35.39	35.65	35.41	35.39
	32.25	34.69	35.01	35.31	35.38	35.38	35.45	35.71	35.62	35.45	35.57	35.78	35.80	35.35
	32.94	34.90	35.16	35.05	35.23	35.36	35.08	35.12	35.20	35.23	35.02	35.12	35.23	35.37
	32.94	35.18	35.81	36.05	36.16	35.82	35.79	35.94	35.97	35.79	35.88	36.02	36.17	35.73
	33.92	35.39	35.55	35.35	35.31	35.32	35.14	34.82	34.87	34.98	34.79	34.61	34.61	34.87
	32.42	34.70	35.38	35.70	35.79	35.82	35.70	35.67	35.43	35.56	35.66	35.52	35.44	35.79
	33.13	35.18	35.26	35.33	35.45	35.42	35.32	35.25	35.35	35.39	35.25	35.19	35.29	35.31
	31.53	34.75	35.23	35.72	35.54	35.33	35.83	36.20	35.90	35.67	35.87	36.07	36.01	35.82
	33.19	34.82	34.96	35.22	35.00	34.94	35.21	35.42	35.25	35.20	35.39	35.42	35.26	35.42
	33.46	35.07	35.14	35.51	35.76	35.70	35.97	35.87	35.94	35.90	35.81	36.06	36.28	36.13
	33.17	34.75	34.89	34.99	34.93	34.86	34.96	35.22	34.93	34.93	34.88	35.17	34.99	34.81

A.2.7 Chapter 7

	Total	Treadmill Belt				Absolute	VO2			
	Body	Speed, m/s			Rest	l/min			Peak	
	Mass	60	75	90	VO2	60	75	90	VO2	
Sub#	kg	FWS	FWS	FWS	l/min	FWS	FWS	FWS	l/min	PAL
1	33.1	1.0	1.3	1.5	0.13	0.45	0.56	0.70	1.12	1.42
2	51.3	0.3	0.4	0.4	0.25	1.19	1.24	1.28	1.37	1.16
3	30.9	0.9	1.1	1.3	0.14	0.51	0.59	0.78	1.38	1.40
4	31.8	0.7	0.8	1.0	0.14	0.47	0.63	0.65	0.88	1.46
5	48.1	0.8	1.0	1.2	0.20	0.80	0.79	0.96	1.15	1.35
6	53.3	0.5	0.7	0.8	0.21	0.76	0.94	0.95	1.12	1.24
7	65.0	1.2	1.5	1.8	0.22	0.80	1.05	1.58	2.57	1.43
8	49.4	0.6	0.7	0.8	0.23	1.34	1.42	1.45	1.45	1.15
9	30.5	1.1	1.3	1.6	0.12	0.55	0.74	1.05	1.42	1.83
10	37.8	0.9	1.2	1.5	0.17	0.59	0.63	0.95	1.71	1.37
11	91.6	1.3	1.6	2.0	0.29	1.64	2.19	2.92	3.45	1.30

A.2.8 Chapter 8

Sub#	BEQ Min1 60	BEQ Min2 60	BEQ Min3 60	BEQ Min1 75	BEQ Min2 75	BEQ Min3 75	BEQ Min1 90	BEQ Min2 90	BEQ Min3 90	Counts/d	Min/d 80%ile	Min/d 90%ile	5min Blocks >80%ile	5min Blocks >90%ile	10min Blocks >80%ile	10min Blocks >90%ile	20min Blocks >80%ile	20min Blocks >90%ile
1	2.00	1.92	1.90	2.29	2.19	2.15	2.09	2.20	2.13	180311	146.7	78.7	15.7	8.7	4.7	2.0	1.3	0.3
2	11.33	11.34	10.83	8.62	8.24	7.88	5.55	7.40	7.57	73728	57.0	15.3	3.7	0.7	0.3	0.3	0.0	0.0
3	2.03	2.03	2.16	2.08	2.31	2.00	2.30	1.96	2.25	157766	129.3	55.3	10.7	1.7	1.0	0.0	0.0	0.0
4	3.39	3.33	3.23	3.29	3.05	2.97	2.91	2.66	2.66	157674	126.3	65.0	10.0	4.7	2.0	1.7	0.7	0.3
5	2.51	2.41	2.33	1.90	2.27	2.11	2.30	2.42	2.31	214240	158.7	96.3	17.3	8.7	5.3	3.3	4.3	0.7
6	7.31	6.50	6.42	4.83	4.99	5.74	4.51	5.14	4.71	120936	89.3	42.0	4.3	0.3	0.3	0.0	0.0	0.0
7	1.46	1.46	1.50	1.53	1.51	1.59	1.73	1.64	1.69	168271	138.7	80.0	18.7	8.0	2.0	1.0	1.3	0.0
8	5.62	5.77	5.71	3.94	4.51	3.94	3.51	3.41	3.38	98431	92.3	24.3	6.3	1.7	2.0	0.3	0.7	0.0
9	1.99	1.99	2.09	2.18	2.24	2.31	1.99	1.99	2.09	290080	238.7	128.7	30.7	9.3	8.7	1.7	1.3	0.3
10	5.41	5.60	5.43	3.65	3.05	3.30	3.57	3.18	3.11	172268	141.7	66.0	14.7	5.0	3.7	0.3	0.0	0.0
11	2.20	2.31	2.18	2.12	2.58	2.28	2.46	2.58	2.31	182515	134.3	74.7	15.3	4.0	5.3	0.7	0.3	0.0